COLUMBIA UNIVERSITY
DEPARTMENT OF ELECTRICAL ENGINEERING

NEXT GENERATION COMMUNICATIONS SATELLITES: MULTIPLE ACCESS AND NETWORK STUDIES

FIRST YEAR FINAL REPORT

BY

T.E. Stern, M. Schwartz, H.E. Meadows,
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16. Abstract

Following an overview of issues involved in the choice of promising system architectures for efficient communication with multiple small inexpensive earth stations serving hetergeneous user populations, this report emphasizes performance evaluation via analysis and simulation for six SS/TDMA (satellite-switched/time-division multiple access) system architectures. These configurations are chosen to exemplify the essential alternatives available in system design. Although the performance evaluation analyses are of fairly general applicability, whenever possible they are considered in the context of NASA's 30/20 GHz studies.

In this phase of research, packet-switched systems are considered, with the assumption that only a part of transponder capacity is devoted to packets, the integration of circuit-and packt-switched traffic being reserved for further study.

Three types of station access are distinguished: fixed (FA), demand (DA), and random access (RA). Similarly, switching in the satellite can be assigned on a fixed (FS) or demand (DS) basis, or replaced by a buffered store-and-forward system (SF) on board the satellite. Since not all access/switching combinations are practical, six systems are analyzed in detail: three FS systems, FA/FS, DA/FS, RA/FS; one DS system, DA/DS; and two SF systems, FA/SF, DA/SF. Results are presented primarily in terms of delay-throughput characteristics.

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SYMBOL LIST

(in order of appearance in text)

Symbol	Definition	Page
C	Available capacity per transponder (bits/sec,)	1.8
N_T	No. of transponders	1.9
N_z	No. of zones	1.10
A,A',B	Traffic matrices and submatrices	1.16
(X,Y)	Input-output terminal pair of switch	1.26
M,N	No. of input and output terminals of M x N connecting switch	1.26
C_T	Total capacity per transponder (bits/sec.)	2.1
N_s	No. of stations per zone	2.1
L	Packet length (bits)	2.1
Δ	Packet transmission time (sec.)	2.1
λ	Average total system traffic (packets/sec.)	2.2
ρ	Mean packet arrivals/slot/transponder	2.8
F	Frame length (sec.)	2.8
P	Propagation time (sec.) [$\doteq$ 0.27 sec.]	2.8
W	Queuing delay (sec. [generic]	
$\overline{W}$	Average weighting time (sec. or slots) in queues [for various schemes]	2.9
$\overline{T}$	Average packet delay (sec.) [for various schemes]	
D_i	Data packet	2.10
R	Request delay (sec.) [order wire]	2.10
$\overline{R}$	Average request delay (sec.)	2.10
R_w	Random delay	2.11
T_i	Trigger signal	2.13
K	No. of data slots per source-destination zone pair	3.2
W	No. of slots per frame	3.1
V	No. of access control slots per frame	3.1
$\overline{Q}$	Expected queue length (packets)	3.1
P(z)	Generating function	3.3
$\theta_t,w,\lambda,\sigma^2$	Parameters in queuing analysis [see Appendix A]	3.3
S	Average of new packet arrivals (packets/frame)	3.9
G	Average channel traffic (packets/frame)	3.9

SYMBOL LIST (cont'd)

Symbol	Definition	Page
k	Retransmission strategy parameter	3.9
g	Success probability of new packets	3.9
q	Packet retransmission success probability	3.9
$d_{\ell/m}$	Probability that ℓ requests are scheduled given m pending requests	4.12
α_ℓ	Parameter in Markov model	4.12
$M(k)$	No. of listed requests before k^{th} slot	4.13
$L(k)$	No. of requests scheduled in k^{th} slot	4.13
$N(k)$	No. of new requests during k^{th} slot	4.13
$P_m(k)$	Prob. $[M(k) = m]$	4.13
a_n	Prob. $[N = n]$	4.13
λ	Packet arrival rate	4.13
P_m	Limiting distribution of $M(k)$	4.14
m_{max}	Finite upper limit on m	4.14
$\mu_m = \overline{L}_m$	Departure rate for queue of length m	4.16
$P_m(t)$	Prob. [queue size m at time t]	4.16
E_m	States of birth-death process	4.16
$\overline{L}_m = \mu_m$	Departure rate for queue of length m	4.16
N	No. of servers and queues	4.21
$\overline{Q}_E$	Expected queue length (used in correction factor)	4.21
$\overline{Q}_I$	Expected queue length for m_{max} [used in correction factor]	
$\overline{Q}_M$	Average queue length for Markov model	4.22
$\overline{Q}_c$	Corrected average queue length	4.22
ℓ	Mean arrivals/slot/destination	Fig. 4.14
Q_M	Finite buffer size	5.6
P_{ov}	Overflow probability	5.7
$\overline{D}$	Mean packet delay (sec.)	Fig. 6.1
q_ℓ	No. of queued requests before ℓ^{th} frame	A.1
x_ℓ	No. of new requests during ℓ^{th} frame	A.1
K	No. of available slots/frame	A.1

SYMBOL LIST (cont'd)

Symbol	Definition	Page
$P_r[\cdot]$	Probability of event $[\cdot]$	A.2
$Q_\ell(z)$	Generating function of queue length	A.2
$Q(z,w)$	Function used in analysis of $Q_\ell(z)$	A.3
$A_r(w)$	Generating function	A.3
θ_t or θ_i	Zeroes of $Q(z,w)$	A.3
σ^2	Variance of arrival process	A.4
$\underline{Q}_p$	Requests already in queue	A.4
$\overline{Q}_p$	Mean requests already in queue	A.4
$\overline{Q}_R$	Average no. of requests already in queue when a group of requests arrive in the mini-slots of a frame	A.4
w	Variable used in queuing analysis	3.3

CHAPTER 1

PROBLEM DEFINITION: ISSUES AND ARCHITECTURES

On July 9, 1979, a study was initiated at Columbia University under NASA support to address problems of multiple access, resource allocation, and network design for next generation communication satellite systems. The first year's effort was directed toward the identification of promising system architectures for efficient communication with multiple small inexpensive earth stations, with emphasis on performance evaluation via analysis and simulation. Two basic sets of requirements shaped our effort. First, the recognition that the next decades will see increasing demand for the two limited resources at the disposal of the satellite system designer: suitable positions in geostationary orbit, and available radio frequency spectrum. Second, the fact that the user populations for these systems will be highly heterogeneous both in their statistical characteristics and their service requirements. Thus, the general thrust of the work has been to attempt to identify the problems associated with the allocation of scarce communication resources in as efficient a manner as possible while satisfying the requirements of a heterogeneous and continually varying community of users. Particular attention is directed toward systems involving large numbers of small "direct to user" earth stations.

While our results are of fairly general applicability, we have attempted to focus the work by considering it wherever possible in the context of NASA's 30/20 GHz studies. Thus, the values of parameters chosen in certain illustrative examples reflect system bandwidths, numbers of antenna beams, etc., that would be plausible in the 30/20 GHz range. In addition, since emphasis is directed to access methods, the impact of bit error rate on throughput is not considered.

In view of the two sets of requirements mentioned above, we have directed our attention toward systems involving a high degree of frequency reuse by means of satellite switched multiple beams with varying degrees of onboard processing. The need for a system that can provide integrated service to a disparate user group ranging from interactive computer terminals to television channels suggests that a highly sophisticated set of multiplexing, multiple access and switching procedures will be required if user needs are to be met economically while using the available bandwidth as efficiently as possible. Therefore, in the first year of this study we have examined a variety of communication procedures, choosing those which show promise of achieving these objectives even though they might appear to be highly complex by today's operational standards.

In this chapter we give an overview of the issues involved in the choice of an appropriate system architecture, including a discussion of user characteristics and requirements, methods of frequency reuse via multiple beams, scheduling considerations, integration of stream and bursty traffic, and switching considerations. The chapter concludes with a brief description of the classes of systems chosen for analysis.

1.1 USER CHARACTERISTICS AND REQUIREMENTS

The vast majority of today's operational satellite systems (the INTELSAT system being the prime example) are designed for voice and video traffic. As a result, they are virtually all circuit-switched systems, using either fixed or demand access, and using mostly analog modulation. Frequency division techniques are generally used for multiplexing and multiple access. Both future technology and new user requirements are likely

to make the existing structures obsolete. In this section we consider briefly the impact of the projected user environment on future syst architectures.

Table 1.1 illustrates the characteristics and requirements of some typical classes of users: voice, video, and a number of different types of data communications services. Note that the statistical characteristics vary widely. Voice, video and certain types of computer data are "stream type" while others, e.g., interactive terminals, transaction systems, etc., are essentially "bursty" in nature. Required bandwidths vary widely, from tens of bits per second for interactive computing to megabits for video. Some applications are unidirectional (e.g., commercial television), while others require full duplex connections. For almost all classes of users significant reductions in required channel capacity can be achieved using various techniques, including data compression, statistical multiplexing, demand access, etc. For example, while voice is considered to be stream traffic, its channel utilization factor is typically about 30%, and well-known digital speech interpolation (DSI) techniques can be used to exploit this fact in order to achieve better channel utilization. Similarly, when a voice channel is used for interactive computer data (currently a common practice) the channel utilization factor is far less than 1%. Thus, statistical multiplexing in the form of message or packet switching is desirable here to increase utilization.

As the characteristics of the users vary, so too do their requirements. Voice, video and certain types of document transfer are relatively insensitive to errors in transmission, while computer data is highly error sensitive. On the other hand, voice applications re-uire

stringent control on transmission delays while many "one way" applications such as document transfer are delay tolerant. Stream traffic generally is accommodated most efficiently using circuit switching. However, some applications (most telephone calls) are tolerant of blocking of call requests, while others (commercial television) are not. Clearly, a single communication protocol will not serve this diverse set of users satisfactorily.

Some data extracted from recent studies of demand trends by ITT and Western Union for 30/20 GHz systems [ITT 79, WES 79] are shown in Table 1.2. They indicate that, while data today occupies a miniscule portion of satellite bandwidth, data services will grow at a much more rapid rate than voice over the next two decades. A comparison of the ITT estimates of demand for data services with those of Western Union is revealing. ITT based its 1980 estimates on the use of standard voice circuits for bursty data, with the concomitant inefficiencies in channel utilization mentioned above. Their year 2000 estimates assume improvements in efficiency via networking, but still assume relatively low efficiency of data transmission. (ITT lists data service efficiency factors of .0035 for terminal to CPU traffic, and .02 for CPU to CPU .) Thus the ITT numbers (more than an order of magnitude greater than Western Union) represent the channel capacity required to transmit bursty data if circuit switching (with some networking) is to be used. The differences between these two sets of figures suggest the improvements in efficiency that are possible if architectures and satellite access procedures well suited to the projected traffic mix are developed. While this comparison is somewhat oversimplified, the fact remains that important economies can be expected by addressing the issues of efficient transmission of data (i.e., bursty traffic) on satellite links, as well as the integration of stream and bursty traffic within a common wideband satellite system. The former issue has

been our primary concern during the first phase of our study, while the latter will be examined during the second phase.

1.2 MULTIBEAM FREQUENCY REUSE

A global beam covering the entire area to be serviced is used on most existing satellites. Downlink transmission is broadcast to the entire area with all stations receiving all communications. While such a beam provides universal coverage, it has the disadvantage of permitting at most one frequency reuse (through opposite polarizations). Spot beams concentrate the transmitter energy on a relatively small spot or footprint, and with sufficient physical separation, multiple spot beams interfere minimally with each other, thus permitting the available frequency band to be totally reused in each beam. In addition, the energy concentration of the spot beams results in markedly lower satellite transmitter power with concomitant reduced weight requirements, and smaller earth stations. Spot beam varieties include fixed spot beams, scanning spot beams, and limited-scan spot beams. A fixed spot beam illuminates a single footprint. The Intelsat IV, IVA, and V satellites incorporate fixed spot beams [MAR 77, PRI 78]. A scanning spot beam may be moved to focus on a multitude of different areas at different times. A limited-scan spot beam is constrained to move along a specific path only [ACA 79]. Multiple spot beams of the same or different kind may be used in the same satellite, with onboard interconnection from the uplink beams to transponders and downlink beams. In such systems the connections are sequentially switched in the satellite resulting in a satellite-switched time division multiple access system (SS/TDMA).

In the following we describe various beam combinations which provide either limited or full area coverage.

1.2.1 Limited Area Coverage with Fixed Spot Beams

The simplest multibeam system employs a set of N_z fixed uplink and N_z fixed downlink spot beams with widely separated, relatively small footprints to avoid interference [TIL 68, COO 73, REU 76, JAR 76]. Such a system is suitable for heavy trunking between large metropolitan centers and affords N_z-fold frequency reuse. As an example, Fig. 1.1 shows spot beams illuminating major cities in the continental United States.

1.2.2 Area Coverage with Fixed Spot Beams and One Global Beam

To provide full area coverage, the fixed spot beams may be used in conjunction with a fixed global beam. Various methods have been proposed to eliminate or reduce the interference between the global beam and the spot beams [REU 77A, ACA 78]. For the uplink path these include: (a) adaptive cancellation for each uplink onboard port and

(b) dividing the available bandwidth into two parts, one for the global beam and the other for the spot beams (with reuse). In this last case, transmitter power is increased to offset the reduced transmission rate due to the bandwidth reduction. For the downlink, (a) the beams may be shaped to minimize or cancel interference, or (b) the global beam may be convolutionally encoded, and an expanded form of Viterbi decoding employed by ground receivers. With redundancy coding, the global beam transmission rate is decreased, but N_z-fold frequency reuse

for N_z total beams is again achieved. However, this system has a number of disadvantages [REU 77B]. Firstly, the global beam requires a different transponder and higher power than the fixed spot beams. In addition, if a transponder is provided for each fixed beam, and if these transponders are assumed to have equal capacity for interchangeability and increased reliability, then this capacity must be at least as large as the largest originating or terminating demand of any footprint. For footprints with less than the maximum demand, the corresponding transponders are under-utilized.

Another means of providing full area coverage is to use a number of fixed spot beams in conjunction with a global scanning spot beam [REU 77B, REU 78]. To achieve isolation, one polarization may be used for the scanning beam, and the other polarization for the fixed beams, resulting again in N_z-fold frequency reuse for N_z total beams. As is the case with the global fixed spot beam, if equal capacity transponders are used, inefficient transponder use results with unequal traffic demand.

1.2.3 Area Coverage with Many Spot Beams

In the systems described above for achieving area coverage by using a number of fixed spot beams and one global beam, a relatively small number of fixed beams is used, e.g., 11, to insure minimal interference by geographical diversity [REU 77A, REU 78, ACA 78]. Each fixed beam, by definition, addresses a single footprint or "zone." It is also possible to achieve area coverage with a system with as many footprints as are required to completely cover the entire area, e.g., 100

[REU 78, ACA 78, ACA 79]. An example of such coverage of the continental United States is shown in Fig. 1.2. It is seen that neighboring footprints overlap. In this case, it may not be feasible to have a separate beam with a corresponding transponder for each footprint because there would be too many transponders, resulting in excessive weight, power, and switching and control equipment. Furthermore, if equal capacity transponders are used, with the capacity equal to that of the footprint with largest originating or terminating demand, then gross inefficiencies in transponder usage result for low demand footprints. However, it is possible to have a fewer number, e.g., 11, of simultaneously active beams, with as many transponders. In other words, a small number, N_T, of transponders is shared among a considerably larger number, N_z, of footprints, with the particular set of active footprints changing from one time slot to the next, according to an indicated schedule.

A particularly important result regarding the minimum number of transponders, and transponder efficiency, was obtained by Acampora and Davis [ACA 78]. It is based on the assumptions that (a) transponders of equal capacity are provided, and that (b) the transponder capacity, C, is chosen to be at least as large as the largest originating or terminating demand of any zone, and that (c) the number of transponders is chosen such that the total capacity is at least as large as the total demand. An example is shown in Fig. 1.3, in which the traffic demand for source-destination pairs is shown by the demand on traffic matrix of Fig. 1.3(a). The matrix entry in the i^{th} row, j^{th} column shows traffic demand from zone i to zone j (in slots/frame). Note that the sum of the elements in row 1, representing the originating demand from zone 1, has the largest value, 12, of any row or column sum. Here the transponder capacity C can be chosen as 13, and three such transponders cover the total demand of 39. The result states that it is possible to construct an assignment con-

sisting of a frame of C time slots, such that the total demand is accommodated and that within each slot the transponders are connected to nonconflicting uplink-downlink zone pairs [ACA 78]. Additionally, if the total transponder capacity exactly equals the total demand, then all transponders are active within each time slot, resulting in 100 percent transponder use, as shown in Fig. 3(b). However, we observe that although the minimum number of transponders yields the most efficient transponder utilization, in some cases, a larger number of transponders yields a more efficient bandwidth utilization*. Thus, as shown at Fig. 3(c), use of four transponders permits transmission of the offered traffic in 12 time slots instead of the 13 required with three transponders. In any case, this system results in N_T-fold frequency reuse for N_T active beams, with the proviso that interference between neighboring zones can be mitigated. This can be done by using different polarizations, or by tailoring the schedule so that within each time slot the scheduled uplinks are geographically distant from each other, and similarly for the scheduled downlinks [ACA 78, ACA 79].

1.2.4 Area Coverage with Limited-Scan Beams

Another approach for employing a set of independent scanning spot beams is to divide the area to be serviced into equal demand regions, and to assign a single scanning spot beam to each region. In this way, the Acampora and Davis result indicated above insures that the equal capacity transponders are fully utilized. Acampora, Dragone, and Reudink give a new geometry to achieve equal demand regions. They

*In general, efficient use of both transponder time and bandwidth are significant. For example, a time-bandwidth utilization product might be examined in further research.

define a set of parallel strips with widths varying so that each strip has the same demand [ACA 79]. Each strip abuts only two other regions, and use of alternating polarizations on successive strips provides inter-beam interference immunity. Reported also is an antenna which moves a scanning beam in one direction only along a single strip, and thus is called a limited-scan beam. As the spot beams overlap slightly, an earth station in an overlap area may be assigned to either beam, in order to equalize demand among the strips. Thus, although the beams move in strictly straight lines, the boundaries between the strips are in general not straight lines. An example is shown in Fig. 1.4. For N_z strips, it is seen that N_z-fold frequency reuse again applies.

1.3 PACKET SCHEDULING CONSIDERATIONS

As indicated previously, a multibeam satellite has N_T transponders corresponding to N_T active uplink beams and N_T active downlink beams, which may simultaneously address N_T of N_z possible zones (e.g., spot-beam footprints, limited-scan strips, etc.), where in general, $N_T \leq N_z$. In this section we consider scheduling of packets, where each packet is assumed to occupy one time slot. The scheduling problem has two aspects: 1) scheduling of the satellite switch, and 2) organization of multiple access among all stations within the same zone. In this Section we deal primarily with the general features of switch scheduling, leaving the details of multiple access to later chapters. For any given time slot, each zone has originating demand for packets to be transmitted to various zones, and terminating demand for packets to be transmitted to it. Switch scheduling consists of determining the switch connections for each time slot with the aim of efficient bandwidth utilization. There are two possible of scheduling according to whether or not the satellite has onboard storage for data. Where no onboard storage is provided, a packet from a particular uplink beam is

immediately switched onboard to a particular downlink beam. Because of this immediate flow, scheduling in this case must take into account both the packet origin and destination zones simultaneously. Where onboard storage is provided, the switch scheduling process is effectively replaced by the scheduling of packet transmissions from the satellite buffers on the various downlinks. We discuss each case separately below.

1.3.1 SYSTEMS WITH NO ONBOARD DATA STORAGE

1.3.1.1 Crossbar Switch Model

Where there is no onboard storage, several uplink-downlink pairs may be switched simultaneously, with the condition that the pairs are nonconflicting, i.e., that there be no more than one packet transmitted from each zone, and no more than one packet to each zone. In this case we may model the multibeam operation as N_z uplink beams and N_z downlink beams connected to the vertical and horizontal lines, respectively, of an $N_z \times N_z$ crossbar switch. The switch contains N_z^2 possible crosspoints of the vertical and horizontal lines. A maximum of N_z of these crosspoints may be simultaneously closed, with no more than one closed crosspoint in each vertical line or in each horizontal line of the switch. There are $N_z!$ distinct patterns of closing the maximum number of crosspoints at any given time. We assume that a distinct switch closure pattern is held for an entire time slot. At the end of each time slot, the switch may be reconfigured with a different closure pattern for the next time slot. In this case, multibeam switch scheduling consists of determining which crosspoints are to be closed in each time slot, or equivalently which uplink-downlink pairs

are to be connected in each time slot.

We note that a single crossbar switch appropriately models the scheduling process where there is no onboard storage, but does not necessarily represent the actual switching apparatus. In reality, this equipment may consist of a single switch, or more generally of a "connecting network" of several multistage switches, as discussed in Section 1.5 below. Also, where controllable phased array antennae are used, they in essence incorporate the switching function in their operation, because they are capable of simultaneously forming multiple beams [ACA 78]. In addition, where the number of transponders, N_T, is less than the number of zones, N_z, then the switching operation involves two phases, one to connect the uplinks to the transponders, and the other to connect the transponders to the downlinks. See Fig. 1.5 for the switching arrangements where $N_T = N_z$ and $N_T < N_z$. However, in all of these cases, the scheduling process for uplink-downlink pairs can be modelled using a single crossbar switch.

1.3.1.2 Fixed Scheduling

The simplest schedule changes the switch closure configuration each time slot according to a fixed, uniform sequence, i.e., a frame structure, such that in one frame, each uplink is connected to each downlink the same amount of time. This assumes equal zone-to-zone traffic. This scheduling is inefficient where the zone-to-zone traffic is unequal. To accommodate unequal traffic, the frame may be adjusted to include more time slots for those zone-to-zone paths with greater demand.

Generally, we may estimate a traffic matrix, with the element (i,j) containing the projected traffic from zone i to zone j in packets per

unit time. Based on this data, it is possible to construct a sequence of switch assignments for successive time slots, constituting a frame, and servicing all of the traffic in the traffic matrix. The minimum number of slots in this frame is the largest originating or terminating traffic among the zones, i.e., it is the largest row sum or column sum of the traffic matrix. Ito, et al., give an algorithm which determines a schedule for a frame with the minimum number of slots [ITO 77]. The original article contained some errors. However, with the necessary corrections the approach is sound. The procedure iteratively computes a set of permutation matrices, whose sum is equal to the given traffic matrix. A permutation matrix is one which has at most one nonzero element in each row and in each column. Each permutation matrix specifies the schedule for a number of slots equal to the largest element in the matrix. A variation of this procedure is given by Wu [WU 78]. In this procedure the traffic matrix is first reduced a number of times by a magic square matrix, which has the property of equal row sums and column sums. Such a matrix results in a 100 percent loaded schedule for a number of time slots, i.e., each zone transmits in each time slot. The reduced traffic matrix is then subjected to the Ito, et al., procedure. (This work is related to that of Acampora cited in Sec. 1.2, for the special case $N_T = N_z$.)

Both of these algorithms also attempt to place time slots with the same switch assignments contiguously, in order to minimize the number of times the switch must be reconfigured. This issue is discussed further in Section 1.5 below. We note also that both algorithms are rather complex. However, it is intended that they be applied but once, in the satellite design phase, to arrive at a fixed schedule, which is

then incorporated in the satellite and earth station equipment. It is also possible to provide a few such schedules reflecting varying traffic at different times of the day. In this case, the appropriate schedule is activated by clock, by sensing changing traffic conditions, or under ground control.

1.3.1.3 Slot-by-Slot Dynamic Scheduling

Fixed schedules, such as the ones described above are only efficient on a statistical basis. They are not sensitive to ever-changing traffic demand. Thus, if in a particular time slot, the schedule calls for zone A to be connected to Zone B, and if zone A has no packet to send to zone B at that time, then the bandwidths for that slot in uplink A and downlink B are simply wasted. There is thus strong motivation to provide dynamic or demand scheduling, which adapts rapidly to changing traffic conditions, configuring the switch to permit maximum traffic flow at all times. This is one of the ideas on which our investigations have focused. In our studies, an order-wire facility is assumed for transmitting requests for slot occupancies to an onboard controller. These requests are queued in a list, and at regular time intervals, the controller uses the then current list to determine the switch closure pattern for the next time slot to be scheduled. Bandwidth utilization is maximized if in each time slot the number of crosspoints closed (for actual traffic flow) is maximum.

1.3.1.4 Multiple Slot Dynamic Scheduling

Slot-by-slot scheduling assumes an order-wire protocol in which separate requests for each connection are transmitted. For large systems, the channel capacity used in the order-wire data transmission of single requests may become excessive. Several other variants of an order-wire system are possible. In one variant considered here, requests to each zone are summed either at each ground station, or at a central ground station in each zone.* The central ground station is connected to all stations in the zone with low-capacity ground links. In either case, the sums are transmitted periodically by order-wire to the satellite. For each such period, the sums for all the zones comprise a traffic matrix. From each successive traffic matrix, the onboard scheduler determines the switch settings for a sequence of time slots. These are relayed back to the earth stations, so that at the appointed time, transmission of the data occurs in synchrony with the switch configurations. In this approach, the identity of individual earth stations with particular requests and subsequently assigned time slots is lost. This necessitates some protocol for distribution of the scheduled slots to individual stations in a zone, either by an algorithm universally applied at each station in a zone, or as determined by a central ground control station within each zone.

The onboard scheduling will vary depending upon whether the system is operating with or without a frame structure. For integrated circuit- and packet-switching, the circuit requirement for a periodic assignment of a particular slot is usually taken to impose a frame structure. If no frame structure applies, as in a pure packet system, there are several options for the scheduling process. The first of these concerns whether or not to schedule each received traffic matrix completely, using

*Another variant is used in Sec. 2.4.

as many time slots as are required to handle all the traffic in the matrix. Successive matrices may require different number of slots. This is the procedure followed by the Ito, et al., and the Wu algorithms cited above, although it should be appreciated that these were not intended for demand scheduling. In fact, these algorithms yield an assignment for a set of time slots, thereby defining a frame, which is then applied repetitively. Also, the algorithms themselves are assessed to be too complex and too slow to be used for demand scheduling. Instead of scheduling a particular traffic matrix completely, it is also possible to interrupt the scheduling of a particular traffic matrix, A, as soon as a new traffic matrix, B, has been constructed. Then, add whatever portion, A', of matrix A that has not yet been scheduled to matrix B, and restart the scheduling process. Note that for a system including circuit switching and a frame structure, the scheduling process is quite naturally restarted each frame. Intuitively, the advantage of the restart approach is that the summed matrix, A' + B, is fuller than the matrix A', and thereby will likely yield more assignments per time slot, i.e., more efficient channel utilization.

The tacit assumption made above is that the scheduling proceeds on a slot-by-slot basis, even though the matrix contains multislot data. It is also possible to conceive of a process which seeks to optimize the assignments for more than one slot at a time, taking into account the inter-slot dependencies. If, in fact, we do permit the scheduling for a particular traffic matrix to continue for as many time slots as is required to exhaust the matrix, then the Ito, et al., algorithm is an appropriate one, albeit too complex for demand scheduling. However, if (a) a frame structure applies, or if (b) we other-

wise opt to cut scheduling prior to exhausting a traffic matrix, then this algorithm is not appropriate. To our knowledge this question has not been addressed for either case (a) or (b). Stated generally for the more regular case (a), the question is:

> Given a frame of K slots, an $N_z \times N_z$ traffic matrix, and a system with N_T transponders, what is the optimum switch assignment for the K slots, in the sense of yielding the maximum traffic flow for the frame?

For case (b) the situation is more complicated because the number of time slots to schedule varies and is not known a priori upon entry to the algorithmic procedure, calling perhaps for a strategy based on expected number of slots to be scheduled.

It should be noted that multiple-slot scheduling introduces additional delay to packet handling. However, it is also possible to transmit anticipated rather than actual requests via the order-wire. This will reduce delay on the average, although some efficiency will be lost due to mismatches between estimated and actual traffic.

1.3.2 SYSTEMS WITH ONBOARD DATA STORAGE

Until recently, there has been little published work on multibeam satellite systems with onboard storage. However, NASA-sponsored studies have addressed the feasibility of multiple beam satellites with on-board storage [FOR 79 CLA 79]. A study by TRW proposes a satellite architecture with 18 fixed spot beams for as many large trunking terminals, and 6 scanning beams for area coverage [TRW 79]. Onboard storage of the uplink scanning beam data is included, but no detail is given of the processing. Ozarow analyses a broadcast satellite system with integrated circuit- and packet-switching, with onboard storage of packets [OZA 79]. This is discussed in Section 1.4 below. In the following we summarize some aspects we have addressed in this area.

Systems with onboard storage are similar to store-and-forward nodes in terrestial systems. Packets are transmitted directly to the satellite with no order-wire facility, are demodulated, and stored temporarily, pending downlink transmission. Uplink access may be handled by contention, or by means of a central ground control, which determines which station is to transmit each time slot. (See Chapter 2.) This central control does not take into consideration the destination of any packet. Its purpose is to avoid contention and to keep the uplink as full as possible. The onboard scheduling of the downlink traffic may be done in several ways, with varying degrees of complexity, bandwidth utilization, and ability to handle features such as broadcasting, priority, and circuit assignment.

1.3.2.1 Downlink Scheduling

A possible onboard configuration is shown in Fig. 1.6. Packets are sorted into queues by destination. With this reordering, the scheduling of packets to be output for a time slot consists essentially of picking packets off the various queues, and writing these packets from the memory onto the appropriate output lines. Each of these lines routes to equipment which remodulates and amplifies the baseband signal. In Fig. 1.6 we assume that the transponders are identical and that their number, N_T, is equal to or less than the number of spot beams or zones, N_z. Note that regardless of the number of transponders, no switch, as such, is required to connect the memory to the transponders. This connection is provided by the usual memory-write operation to several output ports. Where there is one transponder per zone, the scheduling process simply initiates transfer of the packet at the top of each non-empty queue to its associated transponder.

However, for a smaller number of transponders, the scheduling process must choose a subset of the non-empty queues to connect for any given time slot. A simple "cycling" algorithm may search successively through the queues, picking the top of the first N_T non-empty queues, starting each search where the previous one left off. This gives faster service to the smaller queues. To equalize delay amongst the various queues, it is probably preferable to use a scheduling algorithm which varies the frequency of output from each queue according to its size. The distribution of traffic among the queues may vary with time. Note that both algorithms result in efficient downlink bandwidth utilization, in that they output N_T packets each time slot, assuming there are at least N_T non-empty queues at each time slot.

1.3.2.2 Queue Storage, Uplink Traffic Control

There are several ways in which the queue storage may be structured. In Fig. 1.6 we show all queues sharing a single random-access memory (RAM). This results in more efficient use of buffer space and/or less interruption in uplink transmission than if the queues are accumulated in separate buffers. However, a single memory is feasible only if the read/write speed is sufficiently high. In either case, each zone transmits continuously (when traffic so demands) unless signalled from the satellite to stop when the amount of free memory falls below a critical point. Restart is also signalled from the satellite when sufficient memory becomes available. Where a single memory is used, it is possible that the satellite could signal all or only a subset of the zones to stop transmission depending upon the strategy chosen and the level of the critical point. In any case, the trans-

mission-interruption algorithm should take into account that the stop and restart signals require 135 ms propagation time to reach the ground, and that during this time uplink transmission continues to occur. If memory overflow and retransmission of packets is to be avoided, there should be sufficient memory left at the time the stop signal is generated to handle the additional uplink traffic that may occur during the indicated propagation time. Similarly, the restart signal should be issued in advance of the availability of sufficient memory to maximize bandwidth utilization.

1.3.2.3 Single-Memory Management

A possible management scheme for the single memory is as follows, as adapted from Chu [CHU 73]. Divide the memory into equally sized blocks, of a size to contain one packet plus a few control bits. A list of the free blocks is maintained, and each new packet is assigned any free block. The assigned blocks for each particular destination are linked into a chain, i.e., each block contains the address of the block that next arrived to the same destination. A queue table is maintained, containing an entry for each destination, giving the addresses in memory of the first and last blocks in a chain. The last block address is required so that when a new packet is placed in memory, its address may be placed in the previous block in the chain. The first block address is used when a block is to be outputted. Upon output, the link address in the output block replaces the first block address in the queue table, and, of course, the block is added to the free-block list. See Fig. B-3 and [CHU 73] for further description.

The memory management scheme indicated above can easily accommodate

various features, such as broadcasting, priority handling, and possibly also circuit assignment. The features and associated data pertaining to each packet can be specified by codes in a packet header. For broadcasting, the header includes the broadcast destinations. This feature can be most easily handled by copying the packet into each of the required destination queues. While this uses memory inefficiently, it is simple processing, which is likely to have a premium over minimizing storage in satellite operation. Alternatively, the packet could be stored once, with a pointer to an auxiliary "destination list." Then when the indicated block is output to one destination, it is removed from the associated destination queue, but instead of being added to the list of free blocks, it is attached to the queue of the next entry on the destination list. Priority handling can be accomplished by ordering the queues by priority, with the highest priorities at the beginning of the queue. Each new packet, M, is "patched" into its destination queue, so it follows the last entry, L, with the same priority. The patching consists of setting the link address of M equal to the link address of L, setting the link address of L equal to the address of M, and, if necessary, changing the queue table.

1.3.2.4 Processing Speed, Reliability

One of the important issues in considering a store-and-forward system centers on the required processing for memory management, scheduling, and other functions. The most likely implementation would be some form of stored program control, permitting changes to parts or even the entire program to accommodate changing conditions, or improvements with new software technology. Provision can be made to transmit

changes from the ground. One question that arises is whether or not the processing can be done fast enough to keep up with heavy traffic loads. In this connection we note that a substantial degree of parallelism may be designed into the control logic. To begin with, the header processing may be done in parallel for all uplink data streams. Also, the various memory management functions can be pipelined. For example, while one packet is being assigned a free block, another packet may be entered into its previously assigned block, and simultaneously the linkage and queue table entries made. In addition, selected processing modules can be implemented with hardwired logic. Yet another question concerns the complexity of the processing, which is considerably more than that of other satellite systems. To increase reliability, various provisions can be made, including regularly scheduled software testing, duplication of program modules, amputation of faulty areas of memory, and ability to bypass optional program procedures. However, in case of severe software failure, we propose a fallback switch, such as shown in Fig. 1.6 with inputs from the N_z demodulators, and outputs to N_T transponders. With this switch controlled by a fallback fixed scheduler, the satellite is effectively converted to fixed assignment SS/TDMA operation. The indicated shunts and start-up of the fallback scheduler would probably be initiated by ground control.

The main advantages of a system with onboard data storage are that it incurs no order-wire delay, can deliver very efficient downlink utilization, and with the required demodulation, it permits additional processing such as forward error correction. The disadvantages are complex processing, extensive storage, unproven space reliability,

and required demodulation and remodulation. While we believe such a system is workable, considerable additional study is required to prove it viable.

1.4 INTEGRATED CIRCUIT- AND PACKET-SWITCHING

As pointed out in Sec. 1.1, stream traffic is usually most efficiently handled using circuit-switching and bursty traffic by packet-switching, and it is possible integrate these two procedures into a common system. The primary motivation for integrating circuit- and packet-switching in a single communications system is to achieve economy by sharing transmission and switching equipment, and by utilizing bandwidth more efficiently [FIS 76, GIT 77, ROS 77]. Other advantages of integration are uniform performance for varying traffic types, economy of scale in transmission leases, more peak capacity for priority use, and flexibility of providing services which combine voice, graphics, data, etc. Most of the studies in integrated systems assume a single TDM channel, and are applicable to terrestial networks or broadcast satellites. Most also assume that circuit traffic unable to be serviced is blocked, while unserviced packet traffic is queued. A primary question addressed is the division of time slots in a frame between circuit and packet use. There are several options for sharing the time slots among the two categories:

- Fixed Boundary--A fixed number of time slots is reserved for circuit use only, and the remaining time slots are reserved for packet use only [FIS 76].
- Movable Boundary--One category (usually circuits) may use up to a fixed number of time slots (less than the total available), and the other category (usually packets) may use the remaining time slots and any unused time slots of the first category.

- Two Movable Boundaries--Each category has a dedicated number of time slots which cannot be used by the other category; the unoedicated time slots may be used by either category [GIT 77].
- No Boundary--Each time slot may be used for a circuit or a packet, but circuit traffic has priority [ROS 77, ART 79].

All of these schemes except the fixed-boundary scheme have the advantage of potentially increasing bandwidth utilization by permitting packets to fill unused circuit capacity. However, the fixed-boundary scheme retains the other advantages indicated above, and is still expected to be more economical than separate networks.

The fixed boundary scheme has been analyzed by Fischer and Harris [FIS 76]. The movable-boundary concept was first introduced by Coviello and Vena [COV 75], and has subsequently been the subject of much study. Earlier analyses indicated that the expected packet delay on a typical terrestrial link was on the order of tens of milliseconds [FIS 76, ROS 77, MIY 78]. It was later discovered that these earlier studies erroneously neglected the frame-to-frame correlation of the number of circuits in progress, caused by the holding time of the circuits, and that because of this the expected packet delays previsouly computed and that because of this the expected packet delays previously computed were grossly underestimated [WEI 77, WEI 79]. In one cited case the erroneous average delay was 20 ms, and the corrected average delay 10 seconds. Large average delays occur in busy circuit periods. If at any point a sizeable number of time slots are seized by circuits, they will continue to be held by those circuits for a holding time. Until a portion of these busy circuits release, the packet queue may build up enormously (over 30,000 in the simulation conducted). While it is not impossible to provide storage for a queue of this size, the data delay is unacceptable. If the circuits are carrying digitized voice, this situation may be alleviated by reducing the voice digitization rate as a function of the voice or data traffic [WEI 77, WEI 79]. Other

possibilities are to detect speech activity, and during periods of silence to use the assigned circuit slots temporarily to send packets, or to reduce the number of speech quantization levels [WEI 80].

A theoretical analysis of the single movable-boundary scheme has been given by Maglaris and Schwartz [MAG 79A, MAG 79B]. Using two different cost criteria involving circuit blocking probability and average packet delay, the movable-boundary scheme was found to be a near-optimal policy for assigning circuits and packets in a fixed frame. Variable frame schemes have also been studied [MIY 78, MAG 78, MAG 79B]. In these schemes, a frame is composed of a time slot for each active (non-silent) voice circuit, and a number of time slots for offered packets, but not exceeding a given maximum total number of time slots. Maglaris and Schwartz have shown this variable frame scheme to be superior to any movable-boundary scheme, but it is difficult to implement because of the lack of synchronization for the circuit traffic.

Another approach for integrated circuit- and packet-switching in a broadcast satellite system was proposed by Ozarow [OZA 79]. In this system the uplink bandwidth is divided into two parts. The major part is a TDMA uplink for circuit traffic. The remaining part is divided into a number of FDMA uplinks, which are randomly accessed by the packets. Non-colliding packets are queued onboard the satellite. The downlink consists of a single TDM channel. Onboard processing stuffs packets into downlink slots not used by circuits. The provision of multiple random access channels results in significantly higher throughput than a single-channel slotted ALOHA system. The entire system results in almost 100 percent downlink utilization. This system depends upon the single channel broadcast ability for each packet

user to monitor the downlink to determine unsuccessful attempts, and retransmit packets when necessary.

The schemes discussed above do not apply directly to multibeam satellite systems. However, our preliminary work on this problem suggests that extensions of many of these ideas to the multibeam case are feasible.

1.5 SWITCHING CONSIDERATIONS

In this section we focus primarily on aspects of physical switching equipment. As indicated previously, we modelled the interconnections between uplinks and downlinks with a crossbar switch, consisting of a set of horizontal and vertical lines, with connections made at the crosspoints of these lines. In more general terms, the interconnection is made with a connecting network, which is any system permitting connections of pairs, (X,Y), where X is an input terminal and Y is an output terminal. A connecting network may be composed of one or several coordinate-array switches. Such a switch is a matrix of switch elements, each of which may be considered the equivalent of a crosspoint of a crossbar switch. In the following we review first some of the types and properties of connecting networks, and then discuss aspects of their use for multibeam satellite switching.

1.5.1 Connecting Networks

In general, we speak of an $M \times N$ connecting network, where there are M input terminals and N output terminals. Such a network may be composed of one or more coordinate-array switches. Networks with more than one switch are generally configured in stages. The switches

in one stage link only to the switches in other stages, and not to each other. An example is shown in Fig. 1.7. The main advantage of a multistage network is that generally it can be implemented with fewer switch elements than a single-stage network consisting of only one switch. Thus, for example, a single-stage network with 32 input terminals and 32 output terminals requires $32 \times 32 = 1024$ crosspoints, but the same connectivity may be obtained with a three-stage network with a total of only 896 crosspoints, as shown in Fig. 1.7.

Connecting networks may be classified according to blocking characteristics as strictly nonblocking, wide-sense nonblocking, rearrangeably nonblocking, and their blocking counterparts. A strictly-nonblocking network is one which can connect any unconnected input terminal to any unconnected output terminal via a path which is distinct from any path used by a currently existing connection. An example of a strictly-nonblocking network is the single-stage switch. A wide-sense nonblocking network is one which can connect any unconnected input terminal to any unconnected output terminal, again via a path distinct from currently used paths, but requires that all connections be made according to a particular routing strategy. A rearrangeably-nonblocking network, or simply a rearrangeable network, is one which can connect any unconnected input terminal to any unconnected output terminal, but which may require momentary interruption of an existing connection to change its connection path.

The thrust of the effort in the theory of connecting networks has been to reduce their complexity while continuing to meet specified connection objectives [BEN 65, MAR 77, KUR 78]. The measure of complexity

most often applied has been the number of required crosspoints. With respect to strictly-nonblocking networks, Clos showed that for $N \geq 24$, an $N \times N$ single-stage switch requiring N^2 crosspoints can be replaced by a strictly-nonblocking three-stage network requiring approximately $X = 4\sqrt{2}\, N^{3/2} - 4N$ crosspoints. The first stage consists of r switches, each of size $n \times m$; the last stage consists of r switches, each of size $m \times n$. The middle stage has m switches, each of size $r \times r$. Where $m \leq 2n-1$, the network is strictly nonblocking. This is the case for the example shown in Fig. 1.7, where $X = 896$. For wide-sense nonblocking networks, existing results are for the most part theoretical. Benes showed that the states of a strictly nonblocking network contain as a subset the states of a wide-sense nonblocking network with the same number of inputs [BEN 73]. Since fewer states imply fewer crosspoints, it thus appears possible, though not yet proven, that an equivalent wide-sense nonblocking network with fewer crosspoints can be constructed from a strictly-nonblocking network. Hwang has investigated routing strategies and minimum number of crosspoints for three-stage Clos multiconnection networks which are wide-sense nonblocking [HWA 79].

An important result concerning rearrangeably-nonblocking networks was first obtained by Slepian [SLE 52], and later generalized by Duguid [DUG 59]. They proved that a particular class of three-stage networks are rearrangeably-nonblocking. The first and third stages each consist of r switches, each of size $n \times n$, and the middle stage has n switches, each of size $r \times r$. If N is twice a square, then the number of crosspoints is $2\sqrt{2}\, N^{3/2}$, which is a little more than half that required by an $N \times N$ strictly-nonblocking network. A 32×32

rearrangeable network is shown in Fig. 1.8, where the number of crosspoints is seen to be 512; compare this to the 896 crosspoints required for the 32×32 strictly-nonblocking network in Fig. 1.7. Subsequently, Benes gave general results for rearrangeable networks consisting of square switches with an odd number of stages. For an $N \times N$ network with N a power of 2, the minimum number of crosspoints is $4N(\log_2 N-1)$ [BEN 65]. For $N = 32$, this is 512. Joel showed that where $N = 2^k$, a rearrangeably-nonblocking network of β-elements (DPDT), requires $2k-1$ stages and $N(\log_2 N)-N+1$ of the β-elements [JOE 68]. For $N = 32$, 129 β-elements are required, and since each β-element can be realized with a 2×2 crosspoint switch, the equivalent number of crosspoints is $4 \times 129 = 516$.

If some degree of blocking is permissible, blocking networks can offer considerable advantage in smaller number of crosspoints and simpler control than nonblocking networks. For example, Kappel discusses networks with 0.001 blocking probability, which give more than a 70 percent reduction in the number of crosspoints required by a strictly-nonblocking Clos network [KAP 67].

1.5.2 Connecting Networks for Multibeam Satellite Switching

We now discuss how the above switching arrangements impact multibeam satellite design. The possible reduction in crosspoints by using multistage networks is attractive for satellite operation, where redundancy of switching equipment is required, and where reduced equipment translates directly into reduced weight, power, and launch costs. However, these advantages may be offset by increased control and memory

requirements. Specifically, assume that for a given time slot, a particular set of uplink-downlink pairs is scheduled for connection. For a single-stage network, e.g., an $N \times N$ crossbar switch, the indicated assignment directly gives the crosspoints to be closed. However, in a multistage network, each uplink-downlink pair must be assigned a routing through the network. Note that here a multiplicity of routings for the set of uplink-downlink pairs is considered at a single time, in contrast to a typical telephone operation, where such routings are handled on a call-by-call basis. If the network is small, and if the number of different sets of uplink-downlink-pairs is small, we may store the routings for various sets in a table. This is, in fact, the procedure recommended in one proposal, which organizes transmission in a fixed frame format, with a fixed number of time slots per frame, and a fixed set of uplink-downlink pairs connected for each time slot [ITO 75], [ITO 77]. The switching mechanism in the proposed system is a rearrangeable multistage network. Although a rearrangeable network is used, in fact no dynamic rearrangements are made. The routings for the set of uplink-downlink pairs in each time slot are precomputed in designing the satellite system, and the sets of routings for the time slots comprising the frame are stored for sequential access.

However, if the system incorporates demand rather than fixed scheduling, storage and access of routings may not be feasible. For, in this case, all possible sets of uplink-downlink pairs may be generated. Since there are $N!$ such sets for N uplinks and N downlinks, even a modest size of $N = 7$ requires 5040 table entries, while $N = 8$ increases this to 40,320. Furthermore, the sets may occur in any order, requiring random rather than sequential access to

the table. Rather than using a table look-up operation, it may be possible to compute the routings at each time slot, using a routing strategy tailored for the particular type of network, be it strictly nonblocking, wide-sense nonblocking, rearrangeably nonblocking, or blocking, as applicable. Additionally, as indicated in Fig. 1.5, if the number of transponders is less than the number of downlinks, then two connecting networks are required, one to connect uplinks to transponders, and the other to connect transponders to downlinks. In this case it may be necessary to store or compute separate routings for each network.

Furthermore, we note that if the connecting networks are of the blocking type, then blockage due to routing difficulties compounds blockage due to switch contention. This latter condition occurs, for example, when two uplinks request connection to the same downlink in the same time slot. In usual telephone operation, of course, such requests are handled serially, with the second one receiving a busy signal. In a satellite context, the second request may also be blocked, or queued for subsequent servicing.

1.5.3 Switch Reconfiguration Time

Another switching consideration concerns the amount of time spent in changing the switch (connecting network) configuration. During this time no data flow may occur, and bandwidth utilization is null. It is accordingly advantageous to minimize the number of times that the switch configuration is changed. Where a fixed frame interconnection schedule is followed, it is possible to place time slots with

the same switch settings contiguously. For example, consider the schedule shown in Fig. 1.3(c). The switch need be reconfigured only after time slots 4, 6, 8, 10, 11, and 12, rather than after each time slot. This means that transmission during the first four time slots, for example, may be continuous. Longer bursts are desirable because they decrease the overhead, guard, and preamble time. For N beams and a given fixed traffic matrix, the Ito, et al., algorithm cited previously results in at most $N^2 - N$ changes per frame in the switch configuration [ITO 77]. Similar results are obtained by Wu [WU 78].

In a demand scheduling situation, it is likely that switch configurations must be changed each time slot. If, however, the scheduling is done on a frame-by-frame basis, it may be possible to group like configurations in successive time slots, and inform all ground stations of the points in the scheduled frame at which the switch will be reconfigured. Since this will in general change from frame to frame, it is not clear that the attendant synchronization is feasible. An alternative is to establish a hybrid frame in which an initial set of time slots has a fixed format incorporating longer and/or different rate bursts, and only the terminal portion is demand scheduled.

We also note that with ever increasing logic speeds, switch reconfiguration time may become an inconsequential issue. Assessments of allowable percentage of total frame time spent in switch reconfiguration have been made as high as 10 percent [TRW 79], and as low as 1 percent [FOR 79]. It should also be appreciated that if controllable phased array antennae are used, reconfiguration time is still required to change the phase shifters. With respect to current capabilities, RF satellite switches with over 500 MHz bandwidth and switching speeds

of less than 50 ns have been built [ROZ 76, LIC 77]. An alternative approach to RF or IF switching is to demodulate the uplink signals, switch at baseband, and remodulate for downlink transmission. A baseband LSI switch is expected to require less space, weight, and power than an RF or IF switch, and offers the capabilities of processing, such as equalization, forward error correction, and allocation of downlink power independent of uplink power transmitted [CUC 77, VIT 77, TRW 79, FOR 79].

1.6 SYSTEMS SELECTED FOR STUDY

The discussion of the previous sections indicates that there is a very wide range of SS/TDMA system architectures that may be appropriate for achieving the stated objectives. In order to keep our effort within reasonable bounds and at the same time obtain performance results of some generality it has been necessary to distill from this great variety of possibilities a small set of configurations which exemplify the essential alternatives available to the system designer. In so doing we have simplified system structures wherever possible, removing as much extraneous detail as possible, as long as it does not effect performance calculations.

In this first phase of our work, one level of simplification has been achieved by separating circuit-switching from packet-switching. In the analysis presented here we deal only with packet-switched systems. However, these are assumed to be part of a larger integrated system in the sense that only a part of the total transponder capacity is devoted to packets, the rest being reserved for circuits. (As mentioned in Sec. 1.4, optimal circuit and packet integration requires

simultaneous consideration of both. However, this issue has been reserved for future study.)

The systems we have studied are conveniently defined in terms of the way station multiple access is handled within each zone, and the way switching is accomplished in the satellite. We distinguish between three types of station access: fixed (FA), demand (DA), and random access (RA). Similarly, the switch sequence can be assigned on a fixed basis (FS), demand (DS) or it can be replaced by a buffered store-and-forward system on board the satellite (SF). As discussion in later chapters indicates, not all station access/switch assignment combinations are practical, and we have narrowed the study down to six: the three FS systems, FA/FS, DA/FS, RA/FS; one DS system, DA/DS; and two SF systems, FA/SF, DA/SF. Chapter 2 describes the structure of these six systems, providing the basis for the delay-throughput analysis appearing in Chapters 3, 4, and 5. The analysis uses approximate queuing models where possible, together with simulation, where analysis fails. Performance comparisons are presented in Chapter 6, followed in Chapter 7 by a summary of our conclusions together with preliminary comments on the second phase effort.

USER CHARACTERISTICS AND REQUIREMENTS

Type	Characteristics	Requirements
Voice	Stream, 64 kbps Utilization Factor 30% Compression, Packetization Possible	Delay Sensitive Error Tolerant Blocking Tolerant
Video (Network, CATV, etc.)	Stream, Wideband Utilization Factor 100% Compression Possible One Way (Video Conferencing Two Way)	Delay Insensitive Error Tolerant Blocking Not Permissible
Data File Transfer Batch Processing Document Transfer (Character)	Stream, Variable Bandwidth Utilization Factor High	Error Sensitive Delay Tolerant Blocking Tolerance (?)
Transaction Systems (e.g. EFT, Airline Reservations) Information Retrieval Interactive Computing Distributed Processing	Bursty, Variable Bandwidth Utilization Factor Low	Error Sensitive Moderately Delay Tolerant

TABLE 1.1

DEMAND TRENDS

WU Impacted Baseline Forecast 18/30 GHz

	1980	2000
Voice (½ ckts x 1000)	3000	20,000
Data (Terabits/Year)	1700	43,000
ITT: Traffic over 200 mi. (Terabits/Year)		
Voice	560,000	3,000,000
Data (Effective)	110,000	440,000

TABLE 1.2

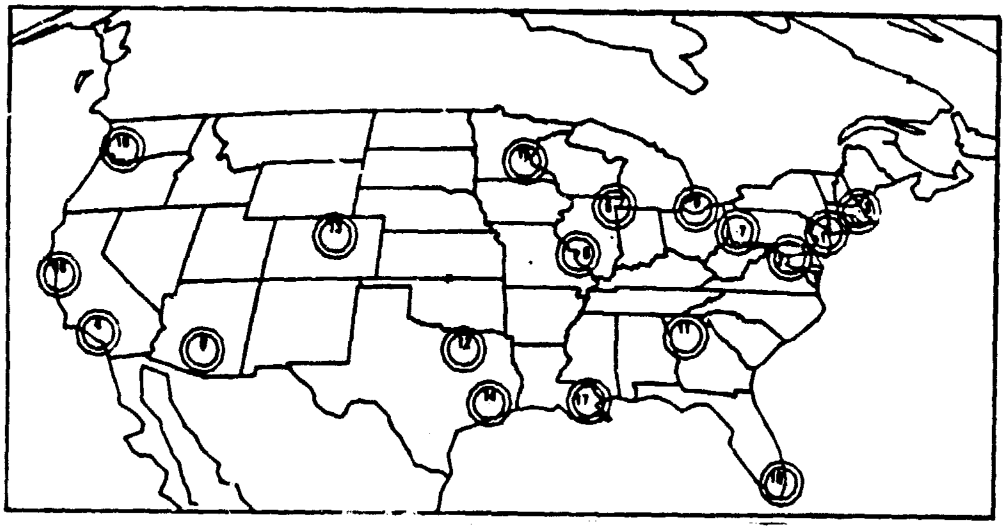


FIGURE 1.1 FIXED SPOT BEAMS COVERING LARGE METROPOLITAN CENTERS

(FROM TRW 79)

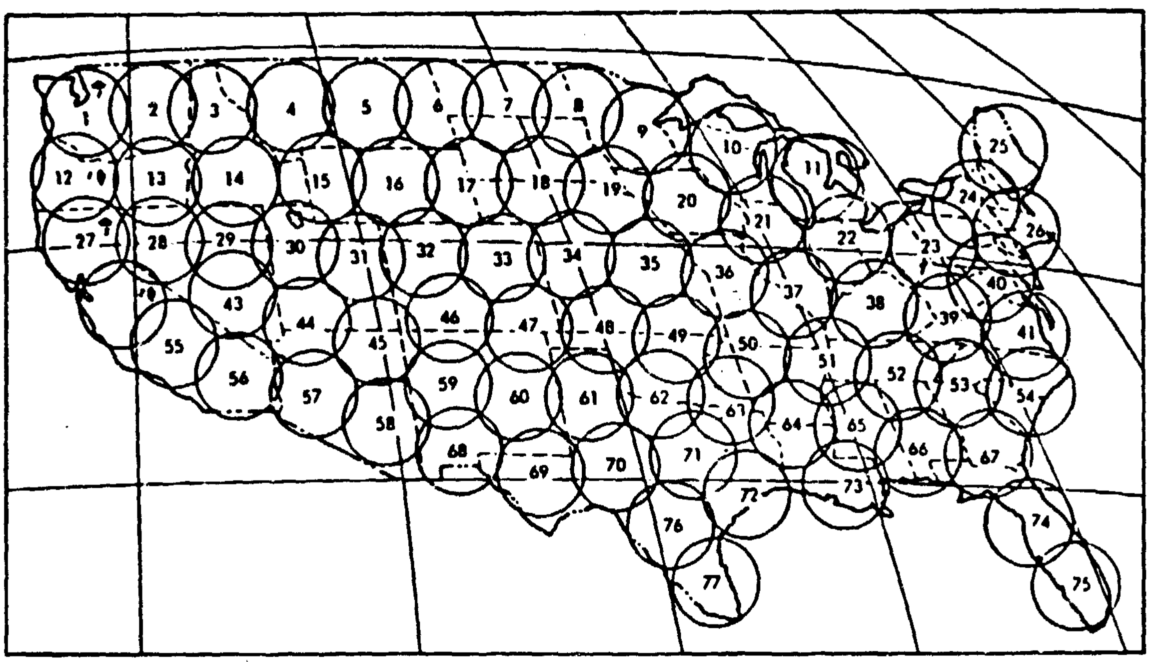


FIGURE 1.2 AREA COVERAGE USING OVERLAPPING FOOTPRINTS

(FROM FOR 79)

from \ to	1	2	3	4	Σ
1	3	6	2	1	12
2	6	4	0	0	9
3	0	1	6	2	9
4	2	0	2	4	8
Σ	11	11	10	7	39

(a)
Traffic Matrix

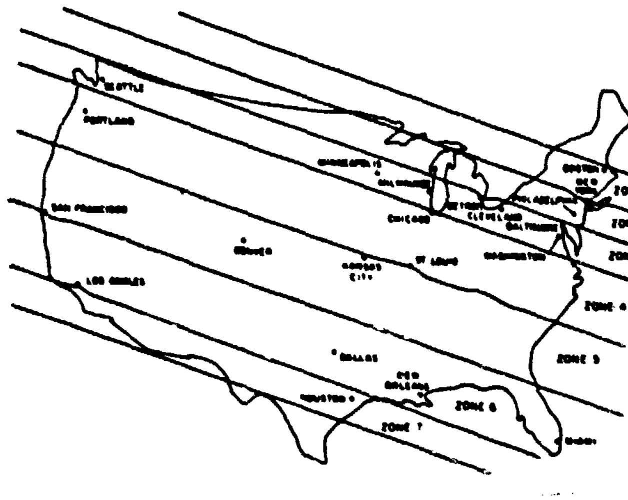
<table>
<tr><th>transponder \ time slot</th><th>1</th><th>2</th><th>3</th><th>4</th><th>5</th><th>6</th><th>7</th><th>8</th><th>9</th><th>10</th><th>11</th><th>12</th><th>13</th></tr>
<tr><td>1</td><td colspan="5">1→2</td><td colspan="3">1-1</td><td colspan="2">1-3</td><td>1-4</td><td>2-2</td><td>1-2</td></tr>
<tr><td>2</td><td colspan="5">2→1</td><td colspan="3">2-2</td><td colspan="2">3-4</td><td>3-2</td><td>3-3</td><td>2-1</td></tr>
<tr><td>3</td><td colspan="5">3→3</td><td colspan="3">4-4</td><td colspan="2">4-1</td><td>4-3</td><td>4-4</td><td>4-3</td></tr>
</table>

(b)
Assignment with 3 transponders

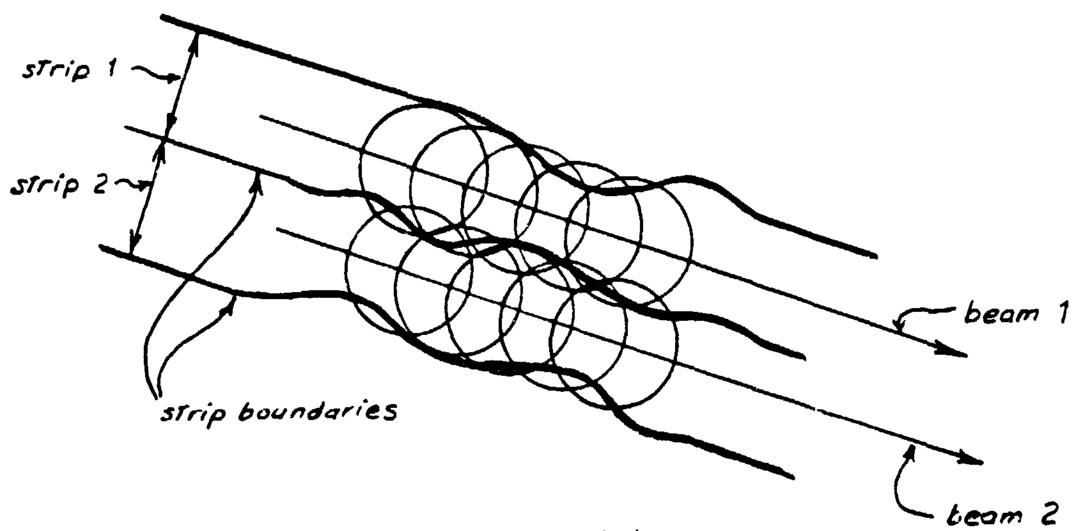
<table>
<tr><th>transponder \ time slot</th><th>1</th><th>2</th><th>3</th><th>4</th><th>5</th><th>6</th><th>7</th><th>8</th><th>9</th><th>10</th><th>11</th><th>12</th></tr>
<tr><td>1</td><td colspan="4">2→1</td><td colspan="2">2-1</td><td colspan="2">4-1</td><td colspan="2">1-1</td><td>1-1</td><td></td></tr>
<tr><td>2</td><td colspan="4">1→2</td><td colspan="2">1-2</td><td colspan="2">2-2</td><td colspan="2">2-2</td><td>3-2</td><td></td></tr>
<tr><td>3</td><td colspan="4">3→3</td><td colspan="2">4-3</td><td colspan="2">1-3</td><td colspan="2">3-3</td><td></td><td></td></tr>
<tr><td>4</td><td colspan="4">4→4</td><td colspan="2">3-4</td><td></td><td></td><td></td><td></td><td></td><td>1-4</td></tr>
</table>

(c)
Assignment with 4 transponders

FIGURE 1.3. EXAMPLE SHOWING ASSIGNMENTS WITH EFFICIENT TRANSPONDER UTILIZATION AND EFFICIENT BANDWIDTH UTILIZATION.



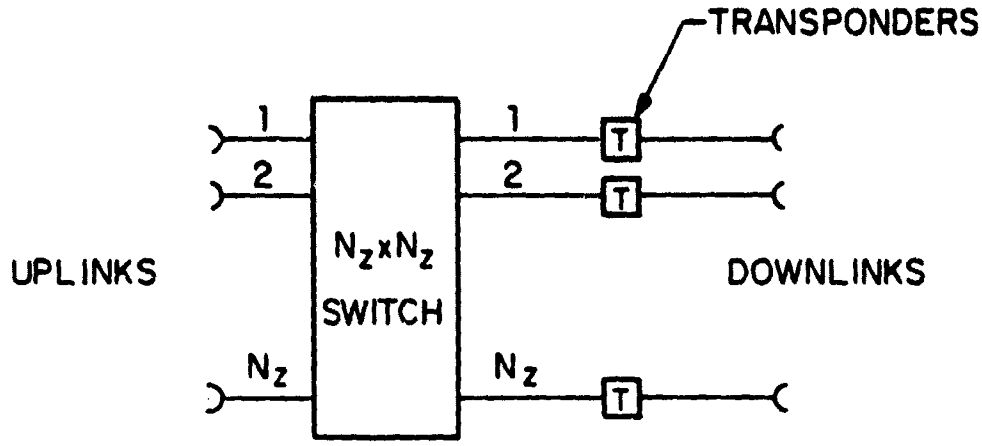
(a)
7 strips with alternating polarizations



(b)
Curved line strip boundaries

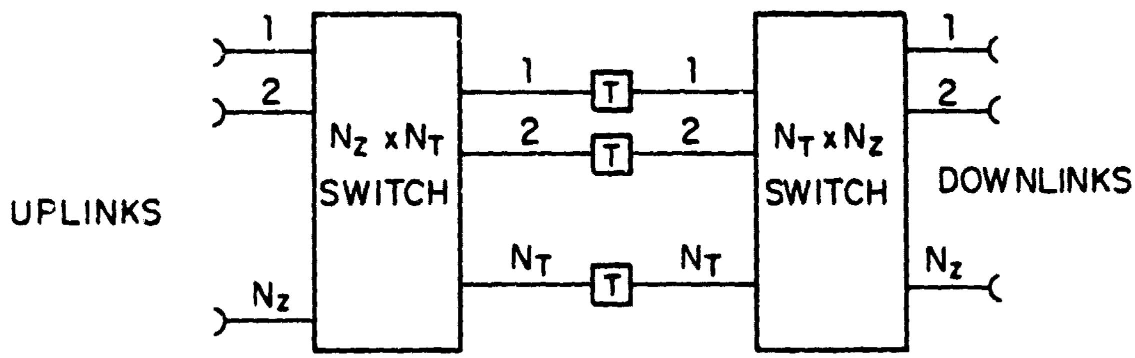
FIGURE 1.4. LIMITED-SCAN SPOT BEAMS WITH EQUAL-DEMAND STRIPS

(AFTER ACA 79)



(a)

NUMBER OF TRANSPONDERS = NUMBER OF DOWNLINKS



(b)

NUMBER OF TRANSPONDERS < NUMBER OF DOWNLINKS

FIG. 1.5 ONBOARD SWITCHING ARRANGEMENTS

A-EL 2112 JD

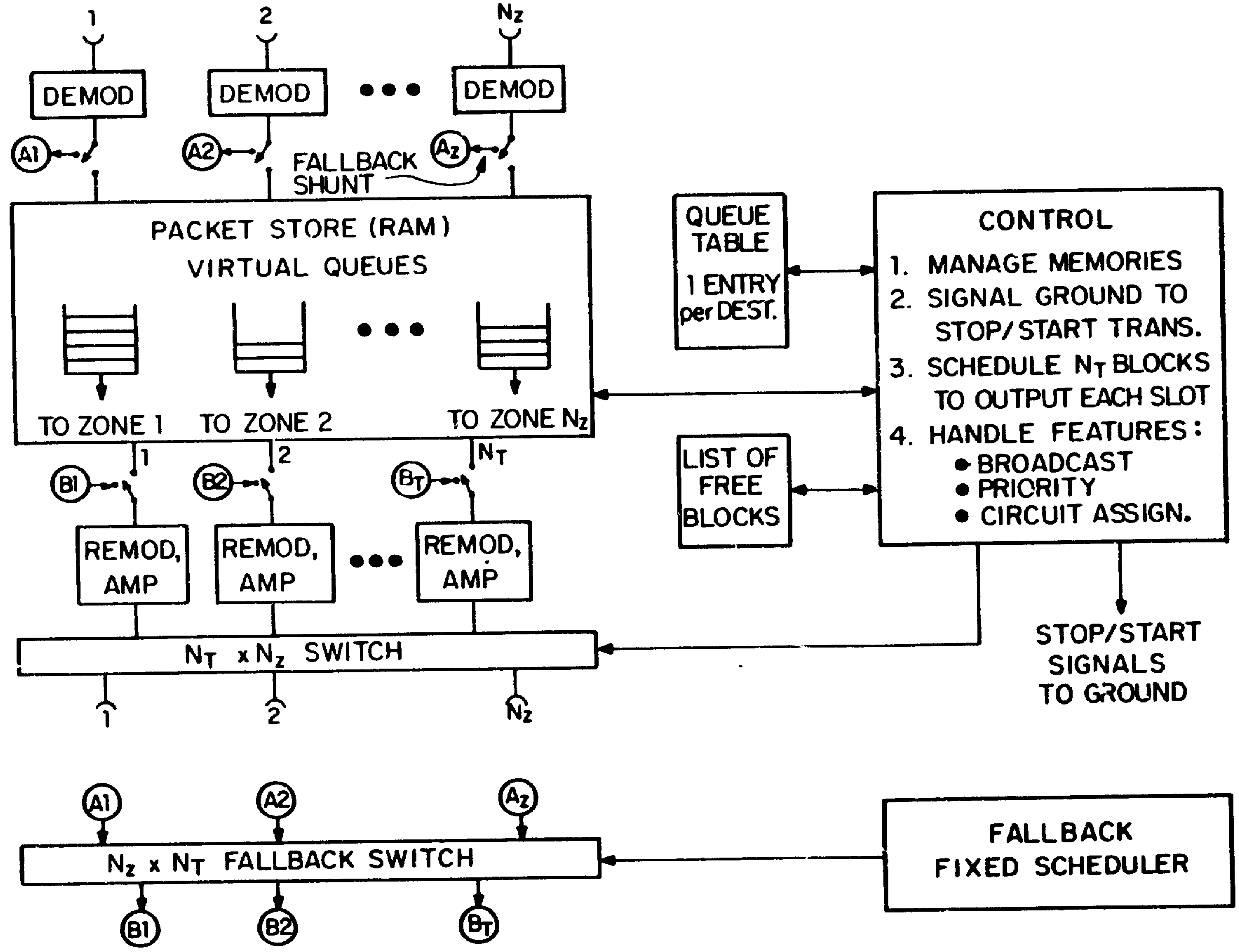
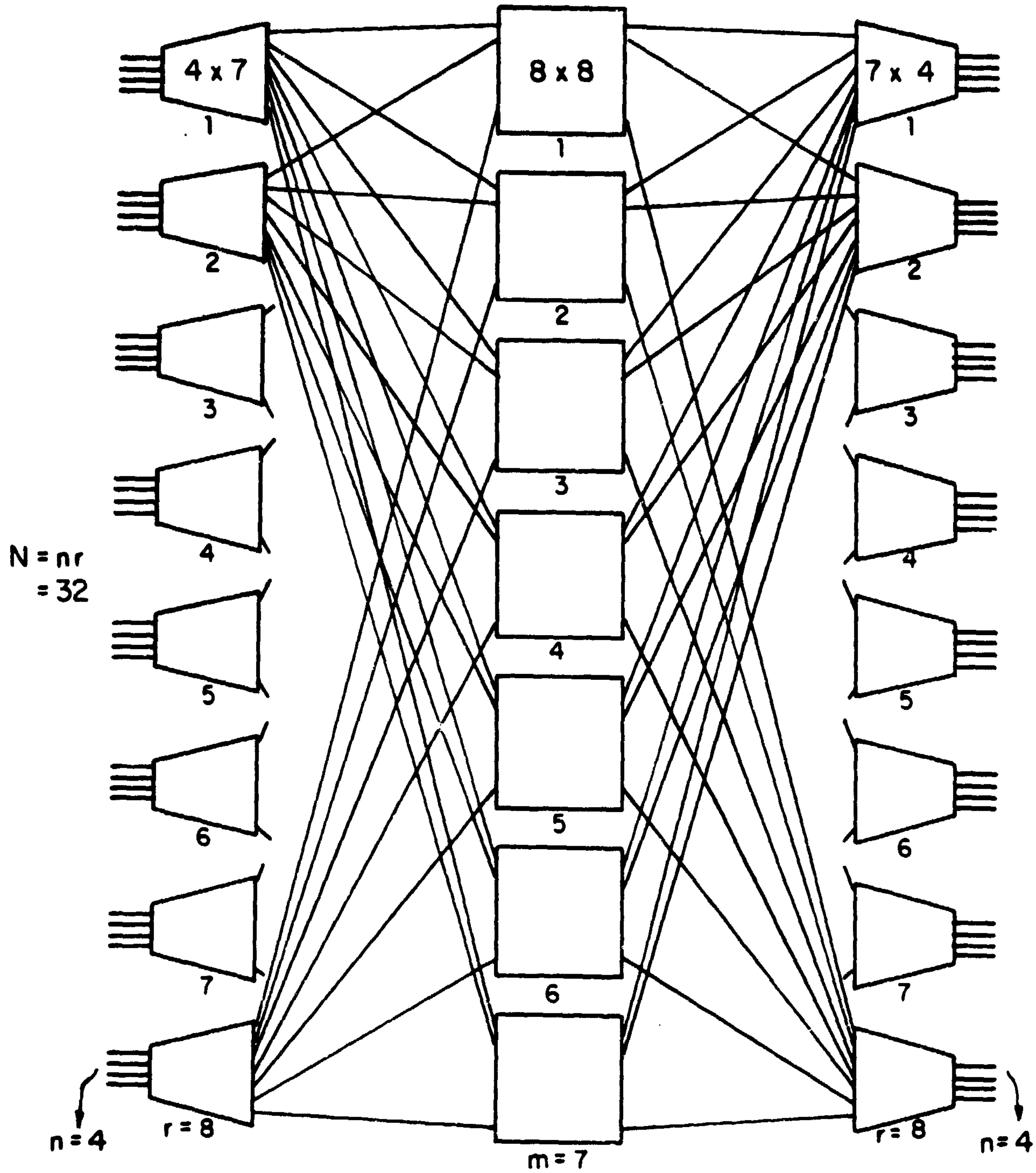
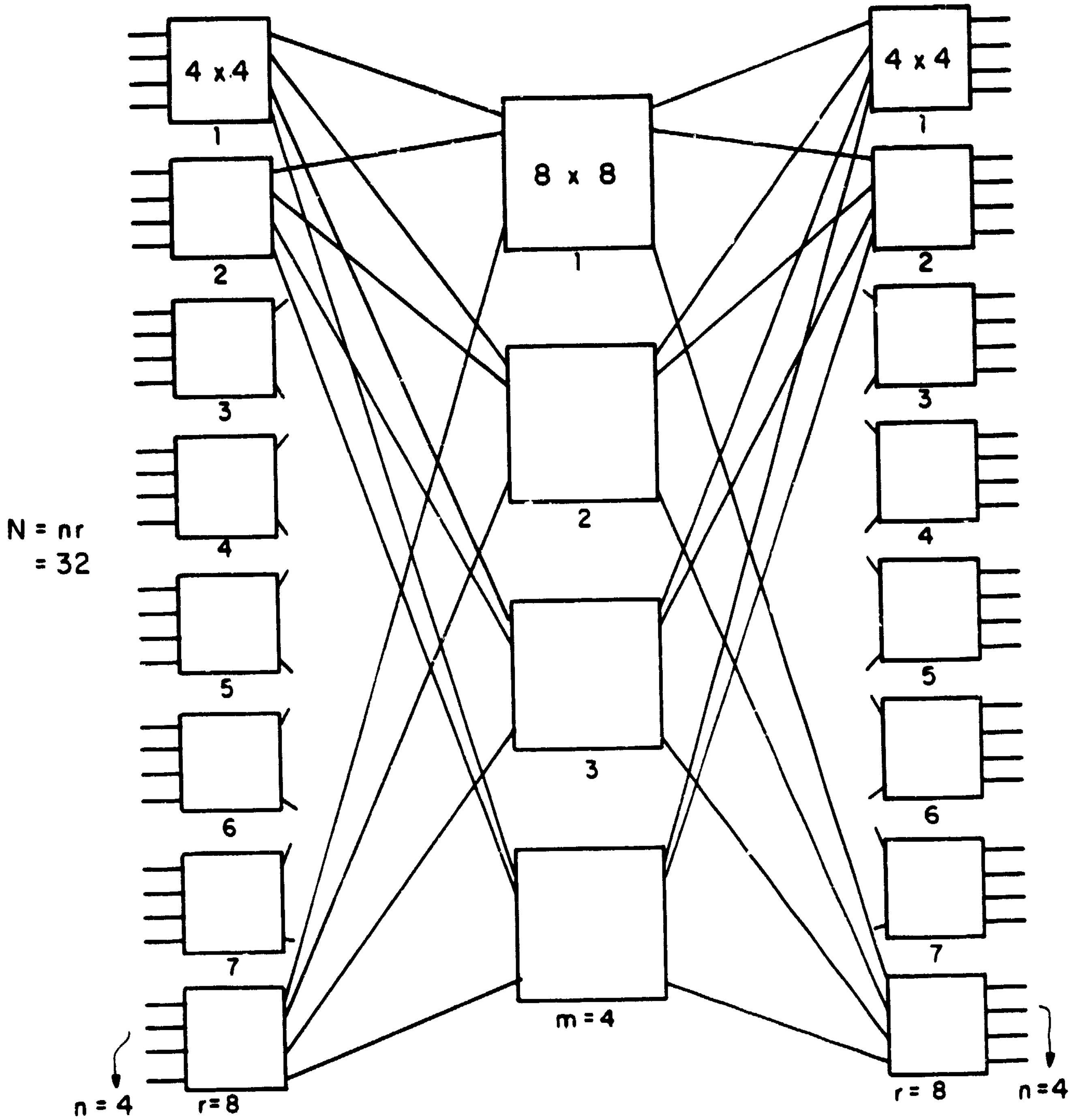


FIG. 1.6 STORE-AND-FORWARD SYSTEM



$$\text{NUMBER OF CROSSPOINTS} = 4\sqrt{2}\ N^{3/2} - 4N$$
$$= (n \times m)2r + (r \times r)m$$
$$= 896$$

FIG. 1.7 A THREE-STAGE STRICTLY NON-BLOCKING CLOS NETWORK



NUMBER OF CROSSPOINTS = $2\sqrt{2}\ N^{3/2}$ = $(n \times m)2r + (r \times r)m$ = 512

FIG. 1.8 A THREE-STAGE REARRANGEABLY NON-BLOCKING NETWORK

A-E - 2111 JD

CHAPTER 2

MULTIPLE BEAM SYSTEMS

In this chapter, we first describe the various structures for the satellite switched multiple beam systems that are considered in our study. We also define the parameters used for analysis and performance evaluation. These include parameters to define the system, the user population and traffic statistics. Some schemes for scheduling of the switching sequence are then described. Finally, we propose multiple access protocols for each of these scheduling schemes and describe their operation. In subsequent chapters these protocols are analyzed and compared.

2.1 SATELLITE SWITCHED TDMA SYSTEMS

In the space segment, we consider a system whose antenna is arranged to form N_z spot beams. Each beam comprises an uplink and a downlink at different carrier frequencies, with connections made between up and downlinks through a switch matrix in the satellite, shown conceptually in Fig. 2.1. There are N_T frequency translating transponders and each connection represents a path through one of them. Each transponder has a capacity of C_T bits per second, with a portion of it, C allocated to our data network. (Recall from Chapter 1 that the packet switched system is assumed to be part of a larger system involving both packet switching and circuit switching.) We assume that there are a number of ground stations within each zone and they are transmitting in a packet switched TDMA mode. We denote the number of stations within each zone as N_s. All packets are of fixed length L(bits), each requiring one time slot for transmission, which we denote by Δ, where $\Delta = L/C$. Messages arrive randomly at the stations and we assume that the message arrival processes at each of the stations are independent Poisson processes. We consider two cases of

message length statistics. In the first case every message consists of a single packet. In the second case, the "multi packet" case, we assume that arriving messages consist of either a single packet or a block of eight packets with equal probability. We let λ denote the total average system traffic in packets/sec. In table 2.1, we list some other symbols used in our study.

We allow for the case where there may be fewer transponders than zones. In the case of $N_T = N_z$, each of the N_z transmit antenna ports has a dedicated transponder. Otherwise, the situation is more complicated, as explained in Chapter 1.

TABLE 2.1 LIST OF SYMBOLS

N_z = Number of zones

N_T = Number of Transponders

C_T = Total capacity per transponder (bps)

C = Available capacity per transponder (bps)

N_s = Number of Stations/Zone

L = Packet Length (bits)

Δ = Slot length (sec.)

λ = Average total system traffic (packets/sec.)

The N_z spot beams can be non overlapping or overlapping as shown in Fig. 1.1 and 1.2. If the beams overlap, the entire service area can be covered but additional constraints on the switching sequence are imposed. For the system with overlapping beams of Fig. 1.2 , for example, it is evident that when zone 74 is transmitting, neither zone 67 nor zone 75 can be transmitting at the same time.

In this study, we will confine consideration to systems with non overlapping spot beams. Note that systems with $N_T \leq N_z$, provide N_T-fold frequency reuse. The multiple access problem in these systems can conveniently be viewed at two levels. First, is the problem of organizing access from all stations within one zone which are contending for the same uplink. We call this the station access problem. The second problem is that of scheduling the satellite switch assignment so that the packets arriving on the uplink are switched to the appropriate destination

down links. This is the switch assignment problem.

The role of the satellite in facilitating station access depends on the ground system configuration. Figure 2.2 shows three possible configurations. The simplest case is shown in Fig. 2.2a, where all stations operate independently, so that any control required for the station access protocol must be handled via the satellite. In Fig. 2.2b, all stations within a zone are connected to a zone control station by low capacity terrestrial links. The control station directs the scheduling of transmissions from all stations in its zone. Finally, in Fig. 2.2c, all users are connected to a single large earth station eliminating the contention problem, but at the cost of a high speed intra-zone ground network.

The degree of onboard processing available in the satellite determines the role it can play in both station access and switch assignment problems. Fig. 2.3 shows some possible configurations with varying degrees of onboard processing. In the simplest case (Fig. 2.3a) the switching sequence follows a prearranged schedule, which might be changed at infrequenct intervals by control signals from the ground . The configuration of Fig. 2.3b allows for switch positions to be scheduled on demand in response to requests from the ground via an "order wire" channel. The order wire can be separated from the data channel on either a frequency or a time division basis. Control signals indicating the scheduled switch positions must also be transmitted back to the ground stations. Fig.2.3c illustrates the possibilities inherent in a system with onboard demodulation and remodulation. In this case, control information from the ground stations can be 'piggybacked' on the data packets, stripped off at the detector and sent to the onboard controller. The controller sets up the switch positions and inserts the necessary control information into the downlink bit stream.

The configurations of Fig. 2.3b and 2.3c are both capable of setting up switch connections on demand, and thus can be used to implement various "slot-by-slot" demand assignment protocols. Still more flexibility is provided in Fig. 2.3d. Here, the system has the ability to buffer packets on board. Thus, the satellite can be used as a store-and-forward node where packets arriving from various uplinks can be queued to await transmission on the appropriate downlinks.

2.2 SCHEDULING OF THE SWITCHING SEQUENCE

Within the framework of the ground and space segment configurations discussed in the previous section, various station access and switch assignment protocols are possible. In this section, we present the switch assignment protocols that appear to be most attractive.

2.2.1 FIXED/QUASI STATIC SWITCHING SEQUENCE (FS)

In the case of a fixed switch assignment scheme, the switch is periodically stepped through all uplink-downlink connections according to a fixed schedule. This can be accomplished without any control channels, using the system of Fig. 2.3a. The frame structure for an FS scheme for the simple case of $N_z = N_T = 3$ is illustrated in Fig. 2.4, where each interval during which the switch position is held fixed may contain many slots. In Fig. 2.4a, we assume that all interzone traffics are equal whereas Fig. 2.4b shows the case of unequal traffic. Note that this frame structure is fixed and is repeated for time frames F sec. long. The switch assignments may be varied infrequently to accommodate slow variations in interzone traffics giving a quasi-static switch assignment. Algorithms for efficient scheduling of the switching sequence were reviewed

in Chapter 1. An efficient schedule is one that accommodates all traffic with a minimum number of switchings per frame and with maximum transponder utilization. We consider the scheduling problem in more detail for a packet-switched system in Chapter 3.

An FS scheme for a system with fewer transponders than zones is illustrated in Fig. 2.5a. The frame structure is shown for a system with $N_z = 4$ and $N_T = 3$. Note that at any one time only three zones are transmitting and three zones receiving. This is further illustrated in Fig. 2.5b which shows the frame structure for the three transponders. In the case of Fig. 2.5, we have assumed that no zone has traffic destined to itself and that all other interzone traffics are equal. This is a simple case in which the switch assignment can be obtained by inspection.

2.2.2 DYNAMICALLY ASSIGNED SWITCHING SEQUENCE (DS)

In this case, the switch assignments are made on demand on a packet-by-packet basis. The stations within all zones send out requests to a controller for transmission slots for arriving packets. The controller makes the switch assignment for each slot dynamically, based on the list of requests currently awaiting scheduling. This scheme can be implemented using the systems of Fig. 2.3b and 2.3c. Note that there is no fixed frame formed since each slot is assigned dynamically. We propose several protocols for switch scheduling by the controller in Chapter 4.

2.2.3 STORE AND FORWARD (SF)

With a system of Fig. 2.3d, buffering is available onboard the satellite and thus, the satellite can be operated as a store and forward node. The structure of an SF system with $N_z=N_T$ is represented schematically in Fig.2.6. The transmissions are demodulated and the received packets are switched to appropriate downlink buffers. Note that in this case, each buffer has a dedicated remodulator and amplifier. Thus, the buffers are serviced continuously. Fig. 2.7 shows an SF system where $N_T < N_z$. Here again the uplink transmissions are demodulated and switched to the downlink queues. However, in this case we have only N_T transponders serving N_z queues and so, the transponders must be shared on a time division basis. (The arrangement of the buffers is shown for conceptual purposes only. The actual storage of packets in a physical memory could involve configurations quite different than those shown in the figures. See Fig. 1.6 for a different arrangement.)

2.3 ACCESS PROTOCOLS FOR FS SYSTEMS

In the last section, we described three schemes for scheduling of the switching sequence. We present multiple access protocols for each of these schemes in this and the next two sections.

In this section we focus attention on FS systems. Various station access protocols are combined with the fixed frame format of these systems to give complete multiple access protocols.

2.3.1 FIXED STATION ACCESS (FA/FS)

We define a FA/FS scheme as one in which a fixed frame format is established with each station allocated at least N_z slots per frame. (One slot corresponding to each destination zone).

The simplest case of an FA/FS protocol is that of balanced traffic, where traffic from each station to each destination zone is the same. In such a case, a frame structure can be used in which each station in a zone is allocated exactly N_z time slots, one for each destination zone. In the case of unequal traffic, slot allocations for various station/zone traffic will differ. The frame format for the balanced traffic case is shown in Fig. 2.8 for the case of $N_z = N_T = 3$. No access control is necessary in this case and a schematic description of the system is shown in Fig. 2.9. Note that each station multiplexes its packets into N_z queues, one for each destination zone. The block labelled MA represents the allocation of time slots to the various stations within a zone. For this system, if we let ρ = mean packet arrivals/station/destination/frame then the frame length F can be expressed as

$$F = \frac{\rho N_z N_s}{\lambda} \text{ sec.} \tag{2.1}$$

A timing diagram illustrating the packet transmission process for this system is shown in Fig. 2.10. A data packet D_i arrives at a station and is queued in the station queue for the appropriate destination zone. After a waiting time of $W_{FA/FS}$ seconds, the packet is transmitted in its time slot. Additional delays of packet transmission time Δ and propagation time P are experienced before the packet is received by the destination station. Thus, the average packet delay in this system is expressed as

$$\overline{T} = \overline{W}_{FA/FS} + P + \Delta \tag{2.2}$$

where

$\overline{W}_{FA/FS}$ = Average waiting time in the station queue.

2.3.2 DEMAND STATION ACCESS (DA/FS)

In the DA/FS scheme, all stations within a zone share available uplink slots on a demand basis. The frame structure is similar to the FA/FS scheme with the difference that slots in a frame are allocated on a zone rather than station basis. Thus, for a balanced traffic case, each zone, rather than each station is allocated N_z slots in a frame and the frame length is reduced by a factor of N_s, viz.

$$F = \frac{\rho N_z}{\lambda} \tag{2.1a}$$

where now ρ represents mean packet arrivals/zone/destination/frame.

In this scheme, all stations which are contending for transmission from the same zone are scheduled on a demand basis. This is accomplished by the use of an order wire channel for each zone. All stations request time slots for arriving messages by means of this order wire. A controller schedules these requests dynamically and the scheduling information is sent back to the stations on the order wire. If the ground configuration of Fig. 2.2a is used, then a fraction of the satellite capacity must be used for this purpose. If this is done on a time division basis, extra slots in a frame must be available for use as the order wire. (See Chapter 3) By switching these slots back to the transmitting zones, a distributed control similar to Roberts' reservation scheme [ROB 73] can be used. However, a drawback of using the satellite channel for the order wire is that in addition to reducing the total available capacity, it also introduces an extra .27 sec propagation delay for all station access control information.

Since we are considering systems in which all the stations that are

contending for transmission are in the same spot beam zone, they are all in a relatively small geographic area. This might make it feasible to use a low capacity terrestrial link for station access control, as shown in Fig. 2.2b. The terrestrial control link has the advantage of low (essentially negligible) propagation delay.

Irrespective of how the control link is implemented, the basic control technique is the same. All stations within a zone send requests for transmission slots to a central controller. The controller forms a queue of all the requests, allocates slots based on some predetermined rule and sends allocation messages to the stations. Fig. 2.11 shows a schematic of this system. A timing diagram is shown in Fig. 2.12. A data packet D_i arrives at a station, which sends a request for a slot indicating the desired destination. After a delay of R sec., the request joins the queue at the controller for the appropriate destination. The delay R includes the propagation delay of the order wire and any queueing delay for access to the order wire. For example, if the order wire is operating on a TDMA basis, control slots are available only periodically and each request message must wait until a control slot is available for its transmission. The request is scheduled after a queueing delay of $W_{DA/FS}$ sec. and the packet is transmitted in the allocated slot. The expression for average packet delay is given by

$$\overline{T} = \overline{R} + \overline{W}_{DA/FS} + P + \Delta \qquad (2.3)$$

2.3.3 RANDOM STATION ACCESS (RA/FS)

This is an extension of the slotted Aloha scheme described in [KLE 73] Slotted Aloha was originally designed for broadcast systems, and the nature of the multiple beam system results in additional complications. First, the RA/FS scheme requires a frame structure similar to the DA/FS scheme. Thus, arriving packets must wait for a slot switched to the appropriate destination. Also, stations cannot hear their own transmission when transmitting to stations in other zones. Thus, a station cannot detect a collision by itself and must wait a predetermined time for an acknowledgement. If, at the end of this "time out" interval, no acknowledgement is received, the station assumes that a collision has occured and schedules the packet for retransmission. Thus, the minimum time needed before a station can detect a collision is twice the round-trip propagation delay.

An example of the timing of the RA/FS scheme is illustrated in Fig.2.13. A packet D_i arrives at a station and is transmitted in the first available slot for the desired destination. It waits for a time out interval for an acknowledgement and if none is received, it assumes a collision and retransmits the packet after a random delay R_W. This time the transmission is correctly received by the destination after a time of $P + \Delta$ sec. The time from the arrival of the packet to the beginning of its successful transmission is denoted by $W_{RA/FS}$. Thus, the average packet delay is given by

$$\overline{T} = \overline{W}_{RA/FS} + P + \Delta \qquad (2.4)$$

Since the throughput attainable in random access schemes is quite low, we consider it in our study only for comparison purposes.

2.4 ACCESS PROTOCOLS FOR DS SYSTEMS

In DS systems, switch assignments are made on a demand basis. To accomplish this, a means is required for the exchange of the necessary control information. As explained in Section 2.1, this could be implemented by the use of the system of Fig. 2.3c, wherein all request information is piggybacked on data packets, stripped off at the detector and sent to the on-board controller. The controller sets up the switch assignment on the basis of a list of requests awaiting scheduling and inserts the allocation information in the downlink stream. Through this allocation, the controller could also resolve station access conflict. However, the problem with this is that a station can send requests only if it has a scheduled data packet.

Another possibility is to set aside some channel capacity for an order wire as suggested in Fig. 2.3b. Since the order wire is already being used to set up switch connections on demand, it can also be used to resolve station access conflicts without any significant additional system complexity. Thus, it is natural to combine demand station access with demand switch assignment (DA/DS), and this is the only DS scheme we shall consider. In the DA/DS system, all stations send request messages on the order wire channel in some predetermined fashion. The following example illustrates the operation of an order wire channel. Consider a system with C_T = 500 Mbps. Assume that a 5 Mbps channel is available (on a different frequency) for orderwire - i.e. 1% of C_T is available for order wire. Let C = 100 Mbps - i.e. 20% of transponder capacity is available for data packets, the rest is for circuit switching- say voice, video etc.

Let the order wire be based on a TDMA frame of length F = 10 ms, with fixed slot assignment for each station in a zone. Then, for example, if N_z = 50 and N_s = 200 stations/zone, we require 200 request slots in 10 ms. This results in a 50 μs/request slots, so that at 5 Mbps, each request packet can be 250 bits long, easily enough to accommodate requests for each destination. Note that the average delay of 5 ms due to the frame size of the order wire is negligible compared to the orderwire propagation delay.

The request messages received on the order wire are demodulated and send to the on board scheduler. The scheduler then sets up switch assignments, resolves station access conflicts and sends allocation messages to the stations. In the example just described, the allocation messages would be transmitted back to the stations on a separate low capacity downlink.

The schematic diagram of a DA/DS system is shown in Fig. 2.14. Each station requests time slots for desired destinations on a packet-by-packet basis. The scheduler sets up switch positions in response to the requests and triggers transmission from the stations whose requests have been scheduled. Variation in propagation time to individual stations, which may complicate the implementation of such a trigger control scheme, is not treated in the analysis below.

The operation of the protocol is illustrated in the timing diagram of Fig. 2.15. A data packet D_i arrives at a station, which transmits a request R_i on the order wire, indicating the desired destination. The scheduler forms a queue of all requests. The request waits on this queue for a time $W_{DA/DS}$ sec. until it is scheduled by the scheduler. At this time, a signal T_i is transmitted by the scheduler on the downlink control channel to trigger transmission of the packet. On receiving the trigger, the station transmits the packet. The average packet delay is expressed as

$$\bar{T} = \bar{R} + P + \Delta \tag{2.5}$$

where

$$\bar{R} = \bar{W}_{DA/DS} + P \tag{2.6}$$

The average queueing delay $\bar{W}_{DA/DS}$ is a function of the algorithm used by the scheduler for switch assignment.

2.5 ACCESS PROTOCOLS FOR SF SYSTEMS

In the SF systems, packets received on the uplink are demodulated and queued in the appropriate down link buffer, determined by control information in the packet header. Station access may be on demand (DA/SF) or fixed (FA/SF).

The system structure of a DA/SF system is shown schematically in Fig. 2.16. Note that there are N_z downlink queues and only N_T remodulator-amplifier pairs to serve them. The FA/SF system is identical except that on the uplink each station has an uplink queue operating independently of other station queues and we have a frame structure where each station within a zone is allocated at least one slot/frame for uplink transmissions.

A timing diagram illustrating the operation of a DA/SF system is shown in Fig. 2.17. A data packet D_1 arrives at a station, which sends a request for a slot to resolve station access conflict. After a delay of R sec. the request joins the queue at the controller. (See Sect. 2.3.2 for an explanation of the request delay R). Note that all requests within a zone join the same queue irrespective of the destination zone. The packet waits on this queue for $W_{DA/SF1}$ sec and it is then transmitted in the allocated slot. After a propagation delay of P/2, the packet joins the onboard queue. After waiting on this queue for $W_{DA/SF2}$ sec,

it is transmitted on the downlink. The average delay is then given by

$$\overline{T} = \overline{R} + \overline{W}_{DA/SF1} + \overline{W}_{DA/SF2} + P + \Delta \qquad (2.7)$$

The average delay $\overline{T}$ for the FA/SF is obtained in a similar way. When a data packet arrives at a station, it immediately joins the station uplink queue. The uplink and downlink times are now denoted by $\overline{W}_{FA/SF1}$ and $\overline{W}_{FA/SF2}$ respectively. Average delay $\overline{T}$ in the FA/SF system is then given by

$$\overline{T} = \overline{W}_{FA/SF1} + \overline{W}_{FA/SF2} + P + \Delta \qquad (2.8)$$

Six access protocols (FA/FS, DA/FS, RA/FS, DA/DS, FA/SF and DA/SF) have been described in this chapter. In Chapters 3,4 and 5, a delay-throughput analysis of each protocol will be presented, and in Chapter 6 performance comparisons will be given as a function of the pertinent system parameters.

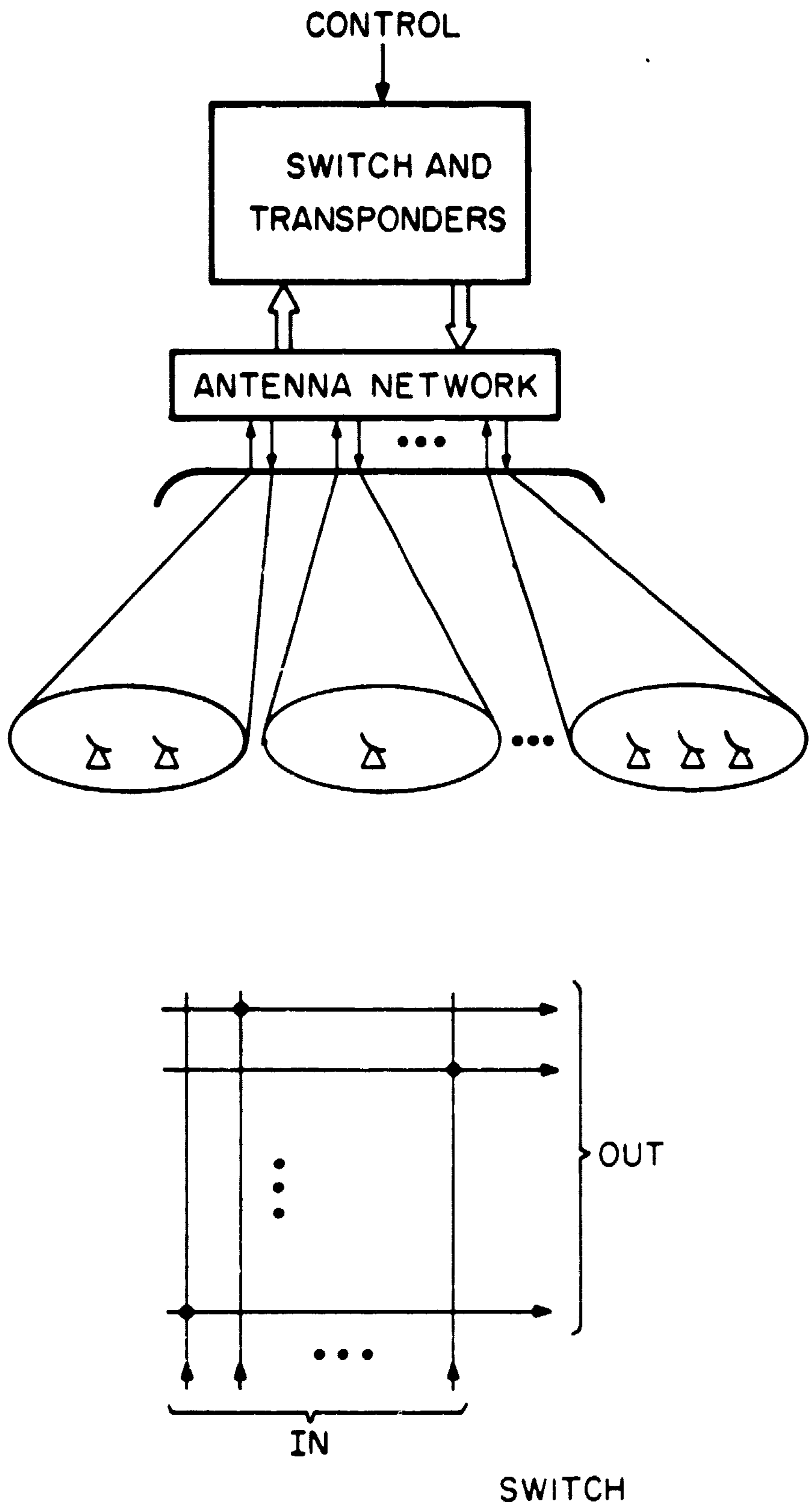


FIG. 2.1 SPACE SEGMENT

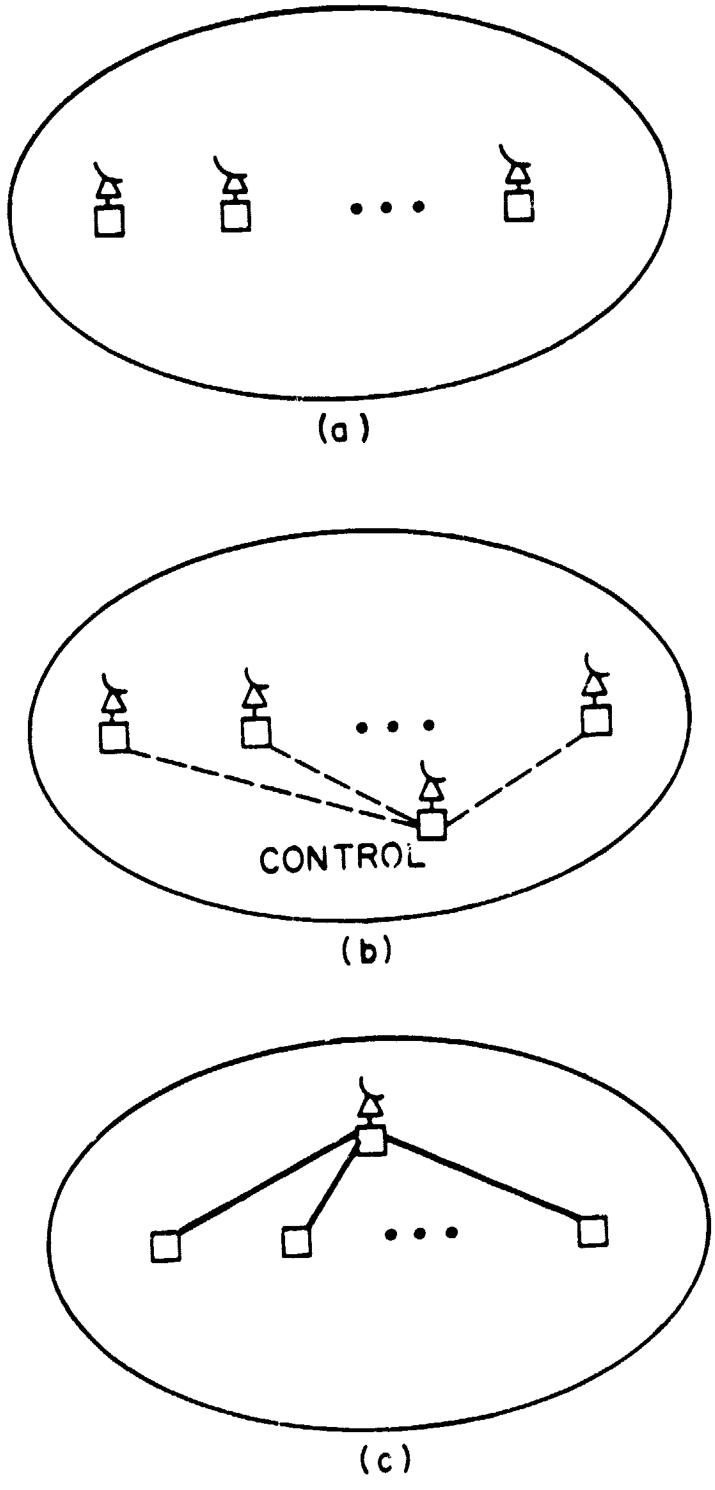


FIG. 2.2 GROUND CONFIGURATIONS

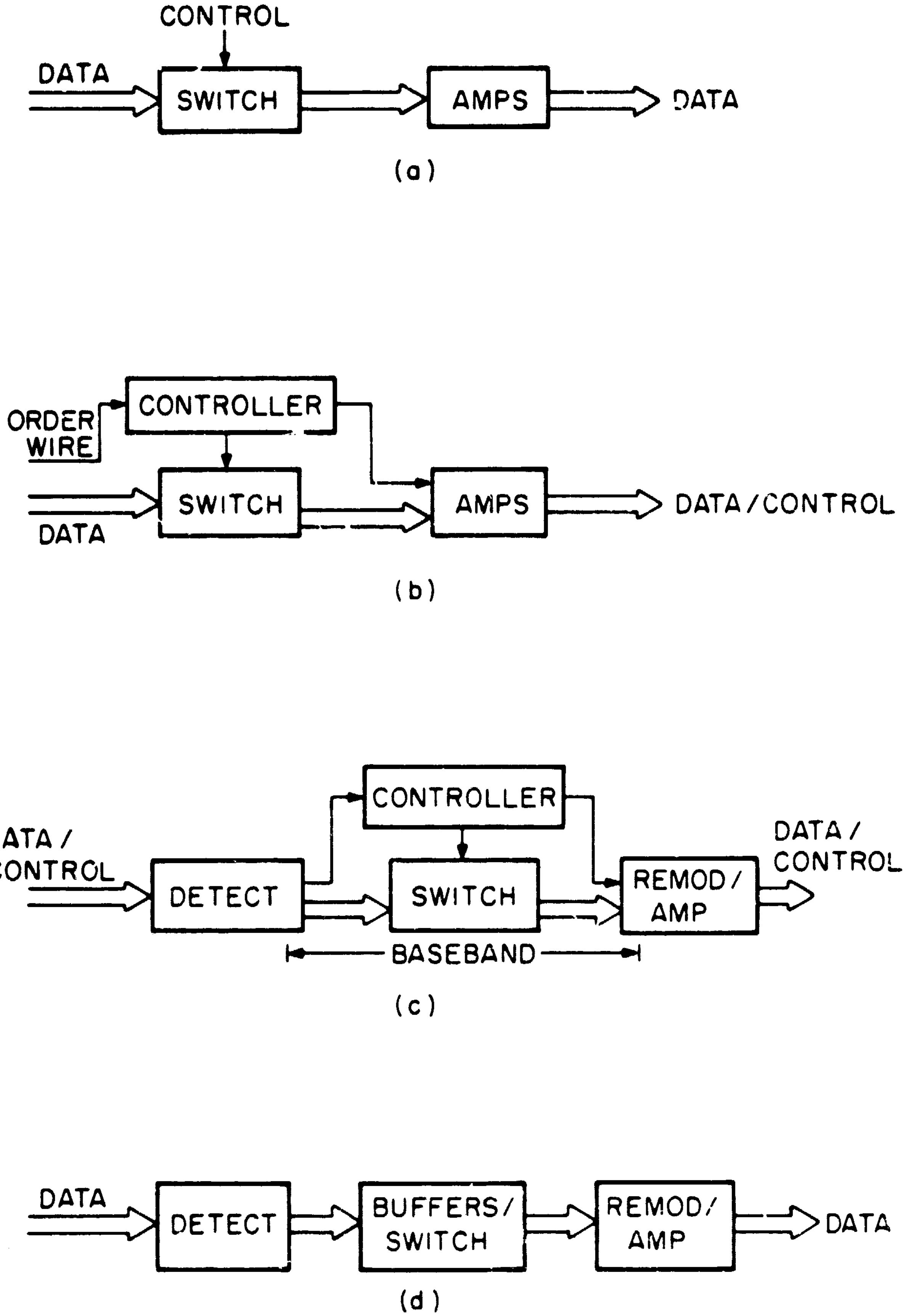


FIG. 2.3 DEGREES OF ONBOARD PROCESSING

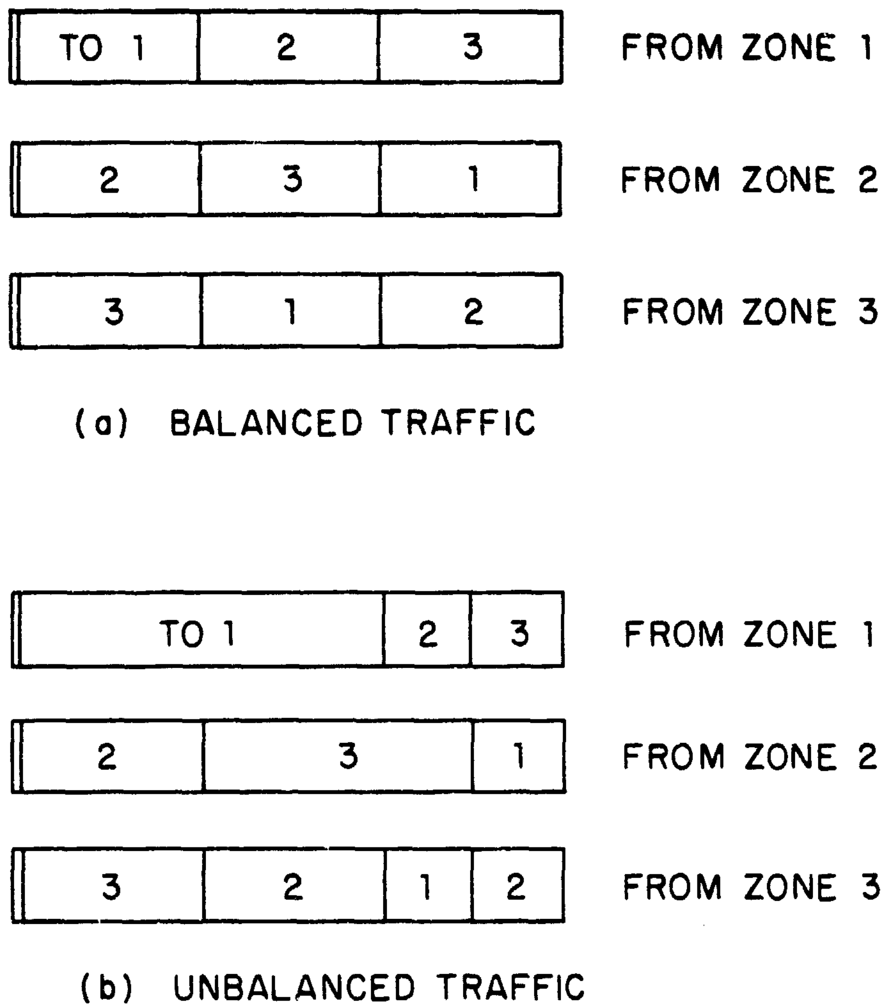


FIG. 2.4 FRAME STRUCTURE FOR FS SYSTEM. $N_T = N_Z$

TO 2	3	4		FROM ZONE 1
3	4		1	FROM ZONE 2
4		1	2	FROM ZONE 3
	1	2	3	FROM ZONE 4

1	1	1	4	UPLINK
2	3	4	3	DOWNLINK

TRANSPONDER 1

2	2	4	2	UPLINK
3	4	2	1	DOWNLINK

TRANSPONDER 2

3	4	3	3	UPLINK
4	1	1	2	DOWNLINK

TRANSPONDER 3

FIG. 2.5 FRAME STRUCTURE FOR FS SYSTEM. $N_T < N_Z$

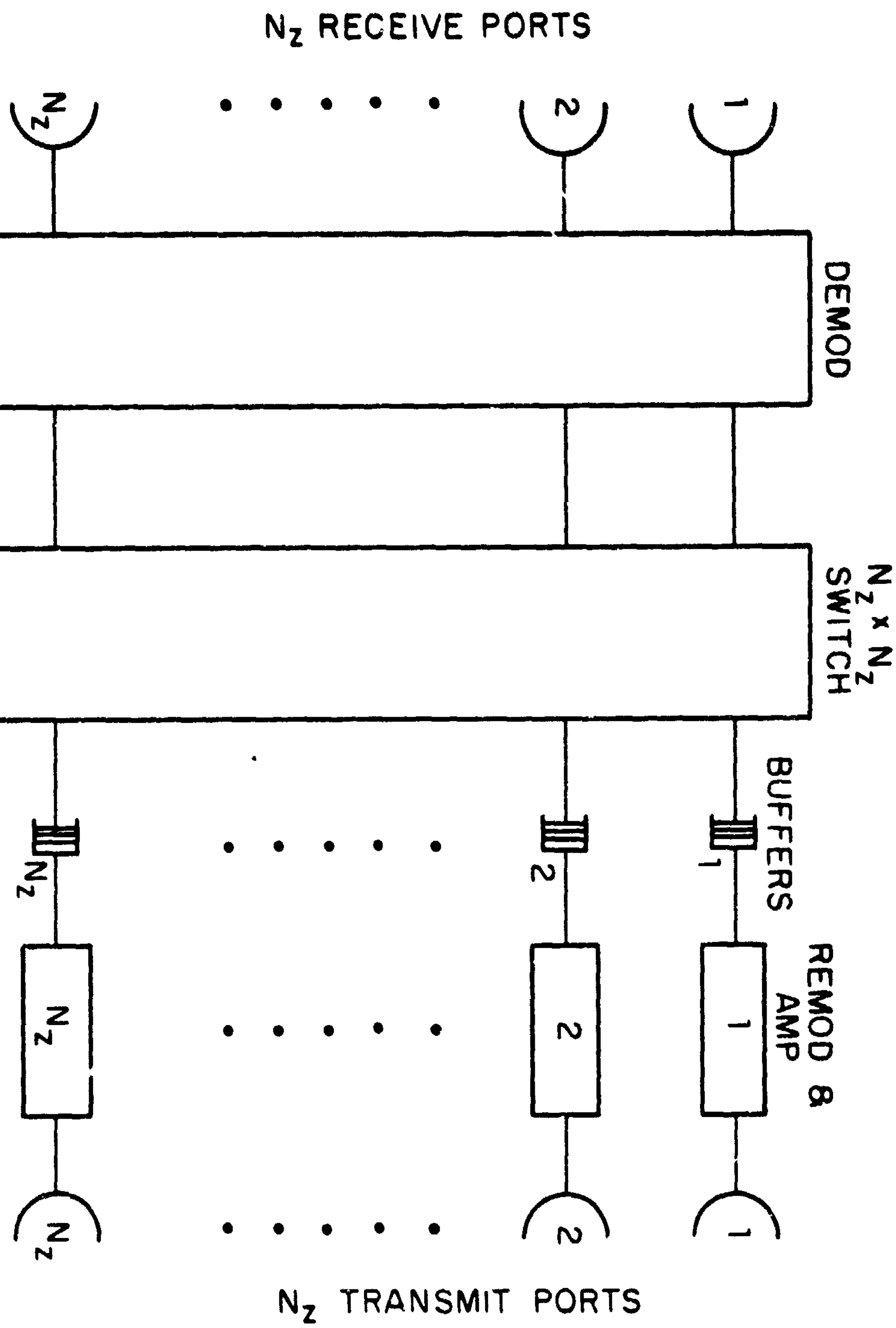


FIG. 2.6 SF SYSTEM. $N_T = N_Z$

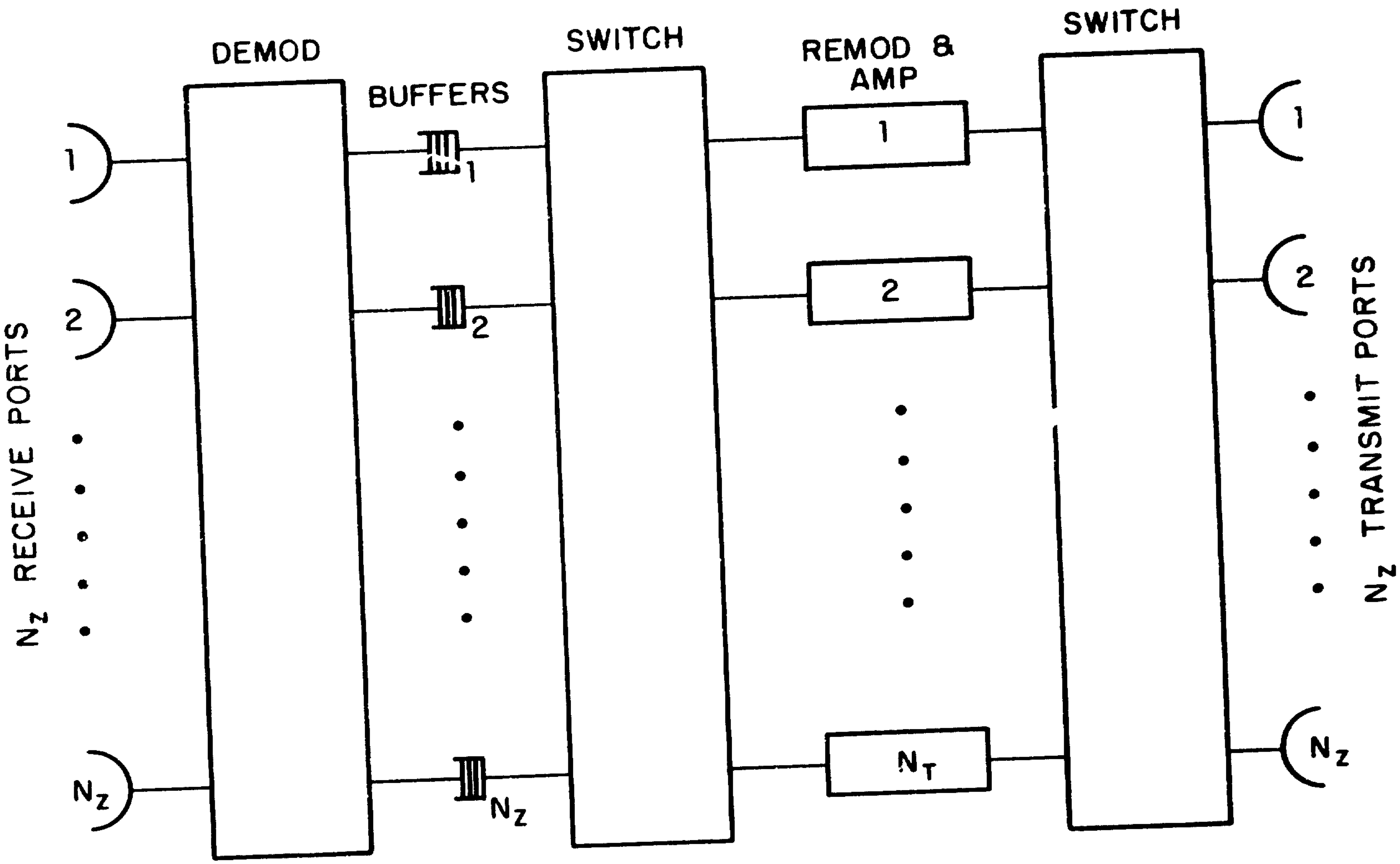


FIG. 2.7 SF SYSTEM. $N_T < N_Z$

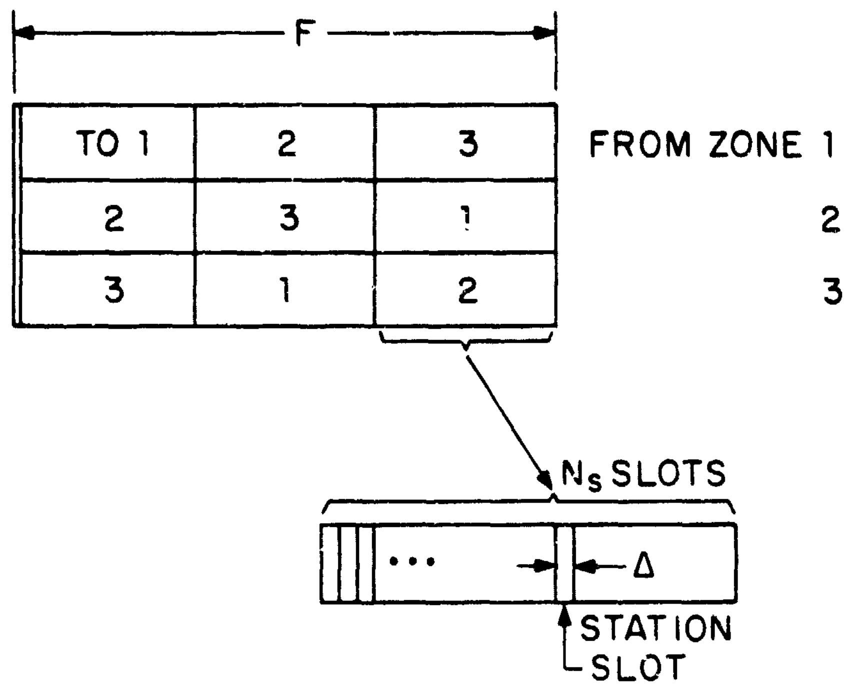


FIG. 2.8 FRAME STRUCTURE FOR FA/FS
(EQUAL TRAFFIC)

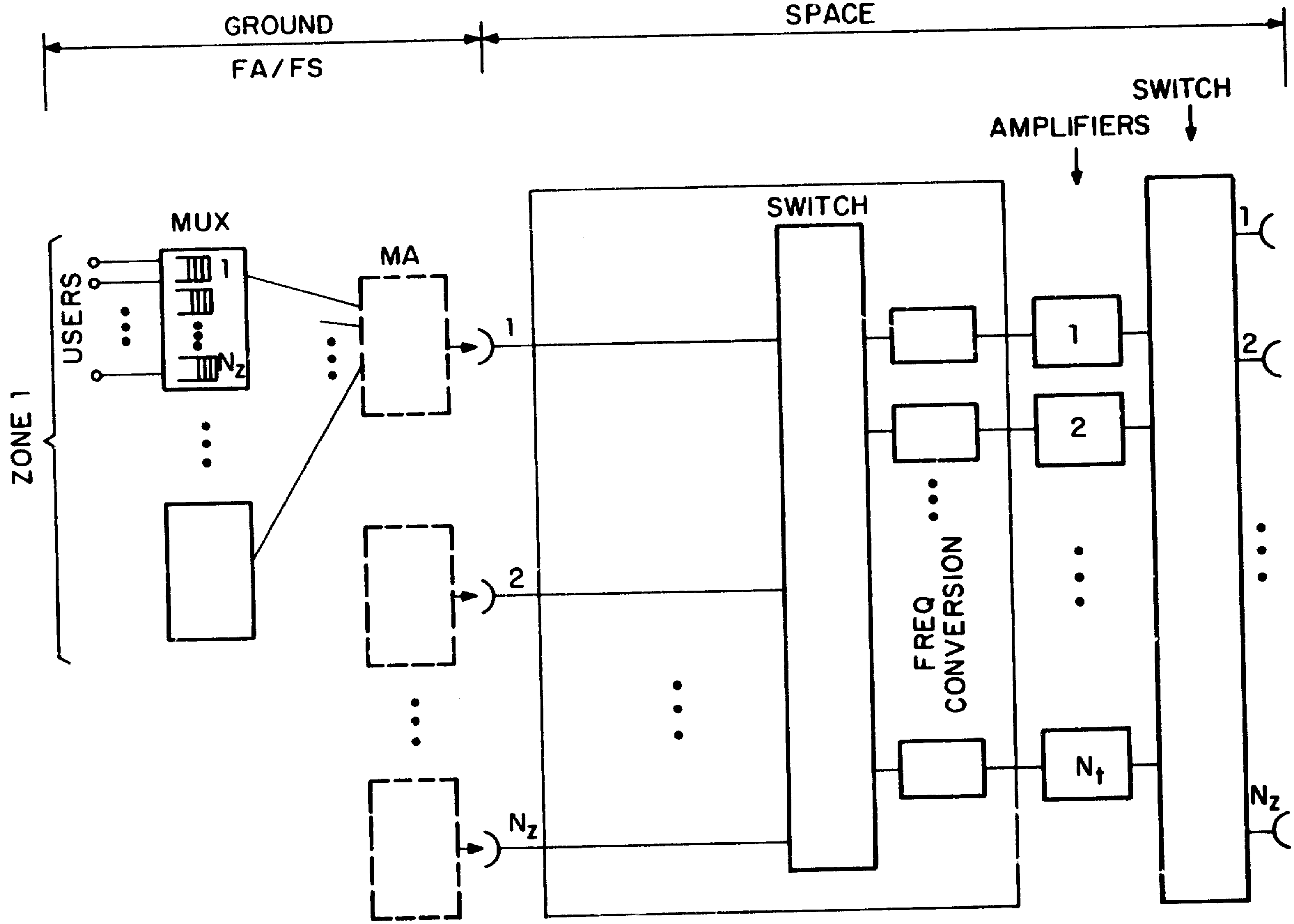
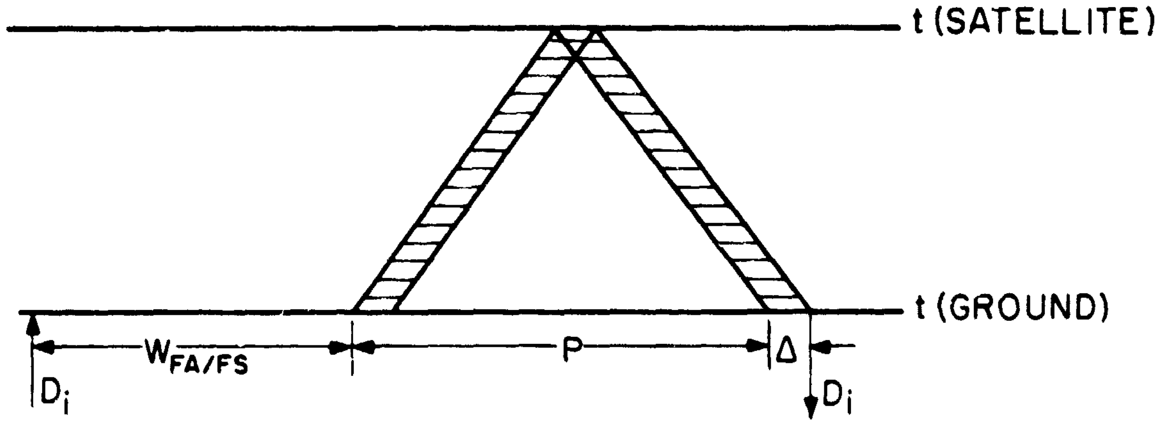


FIG. 2.9 FA/FS SYSTEM



$$\overline{T} = \overline{W}_{FA/FS} + P + \Delta$$

FIG. 2.10 TIMING DIAGRAM (FA/FS)

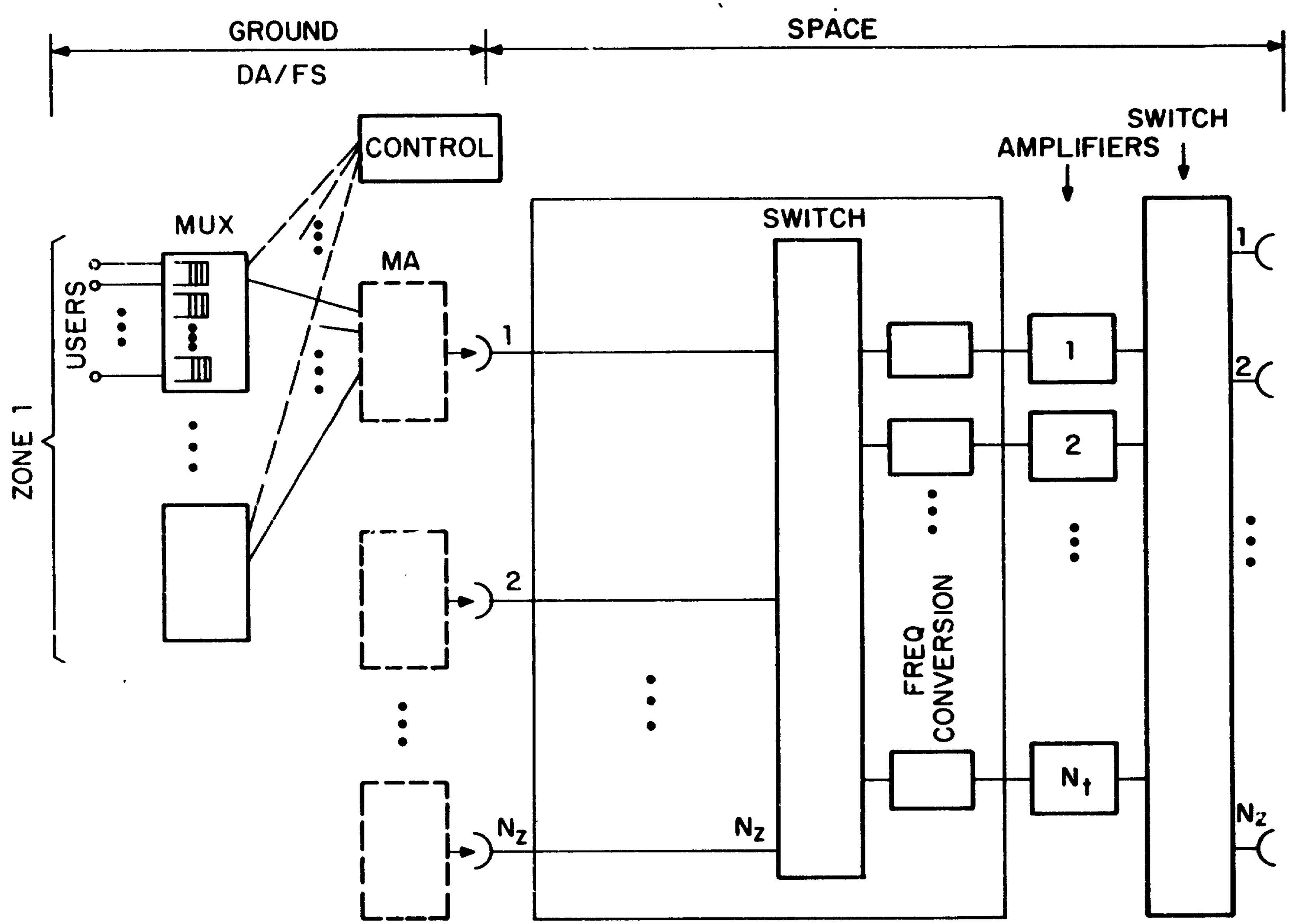
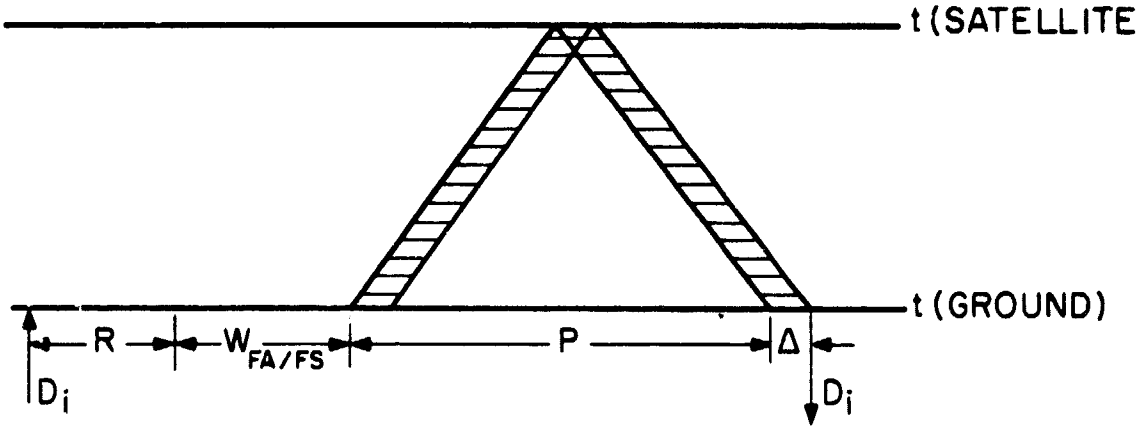
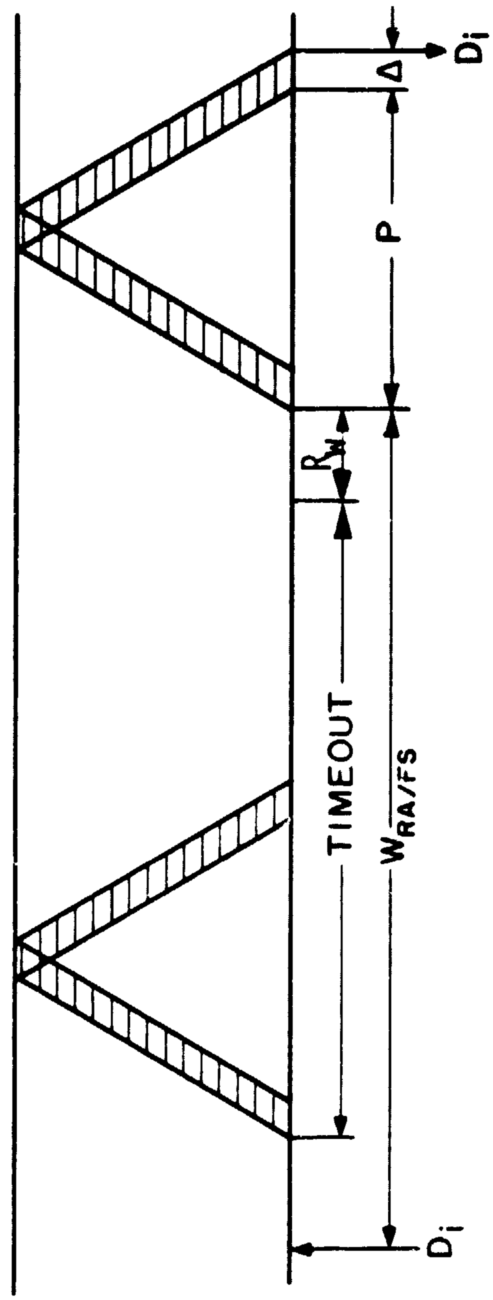


FIG. 2.11 DA/FS SYSTEM



$$\overline{T} = \overline{R} + \overline{W}_{FA/FS} + P + \Delta$$

FIG. 2.12 TIMING DIAGRAM (DA/FS)



$$\overline{T} = \overline{W}_{RA/FS} + P + \Delta$$

FIG. 2.13 TIMING DIAGRAM (RA/FS)

A-EE-1891 W.L.

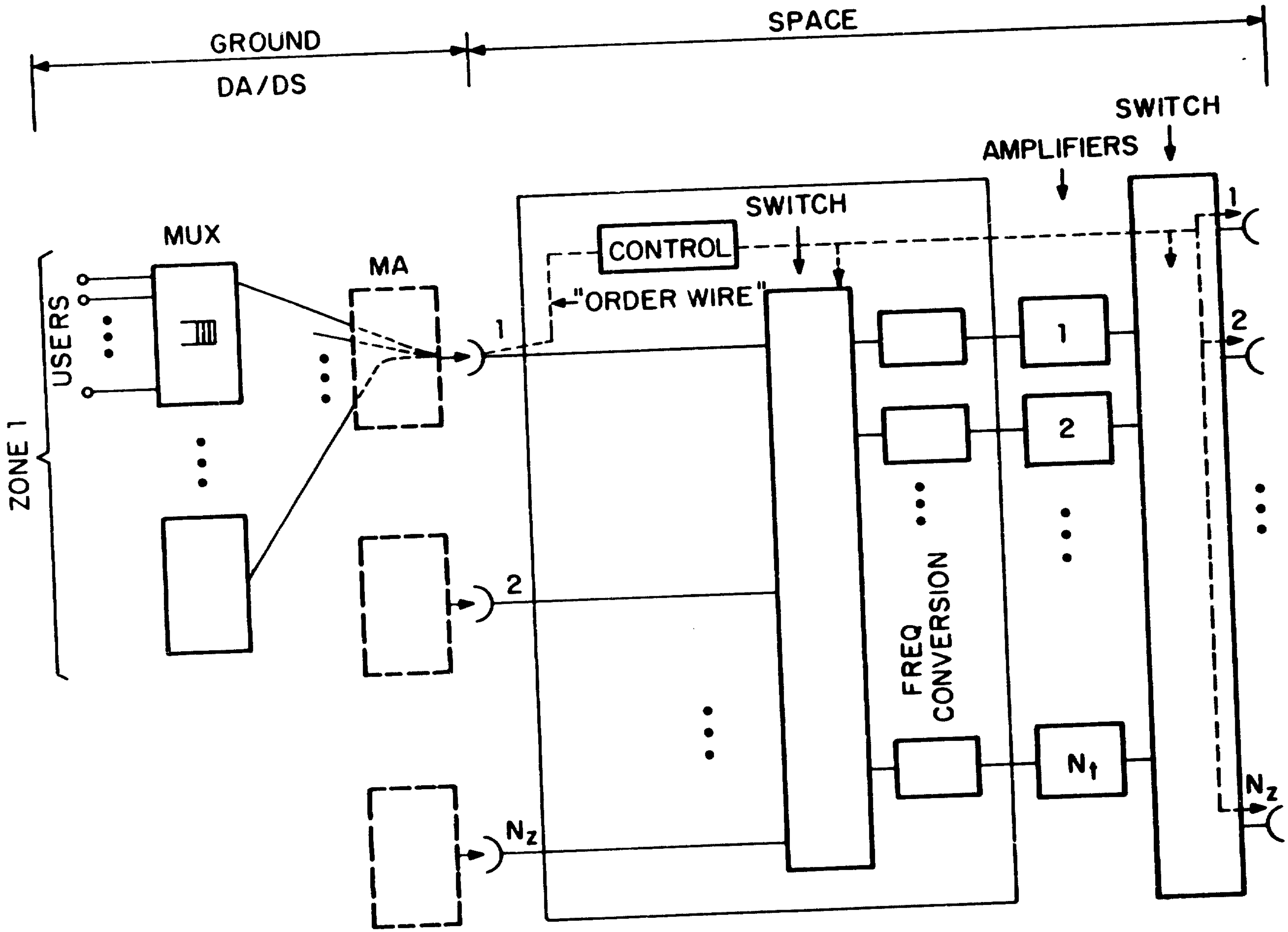
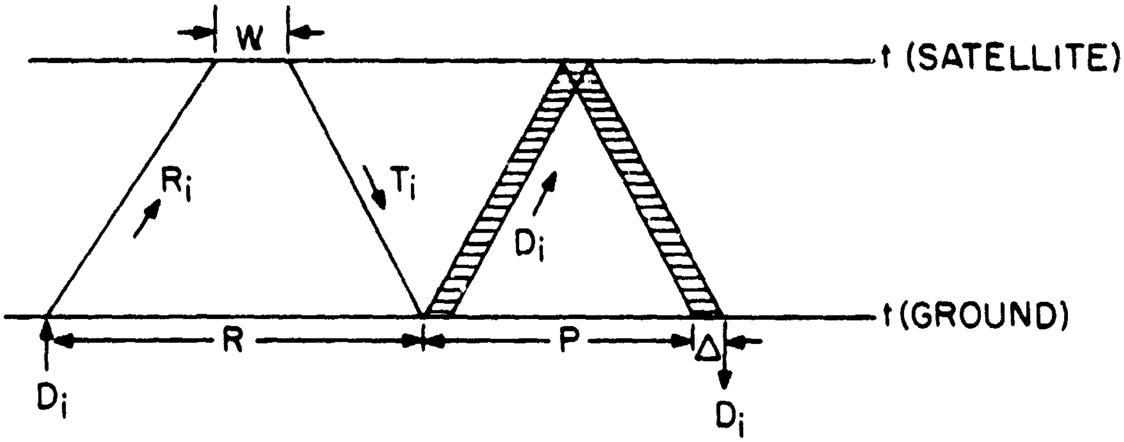


FIG. 2.14 DA/DS SYSTEM

PACKET SCHEDULING (DA/DS)



$$\overline{T} = \overline{R} + P + \Delta$$

$$\overline{R} = \overline{W} + P$$

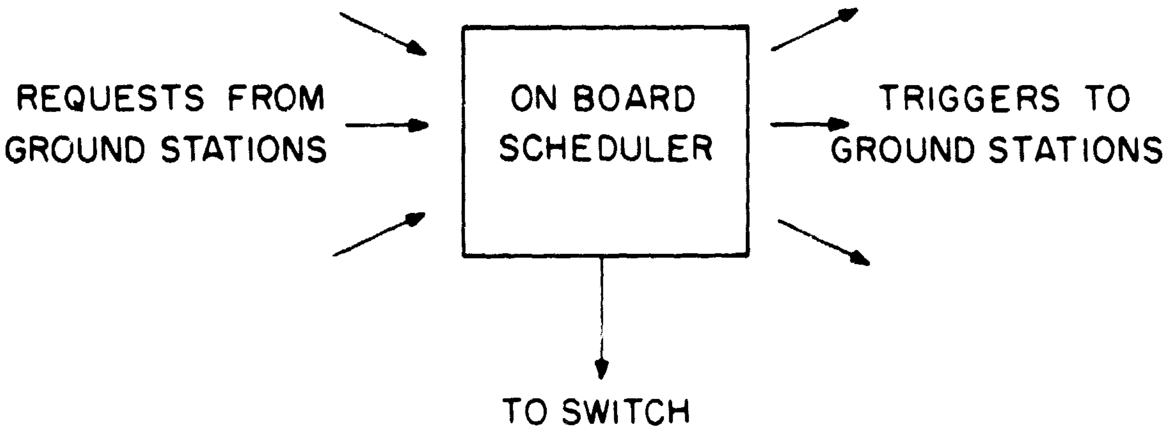


FIG. 2.15 PACKET SCHEDULING IN A DA/DS SYSTEM

A-EE-1892 W.L.

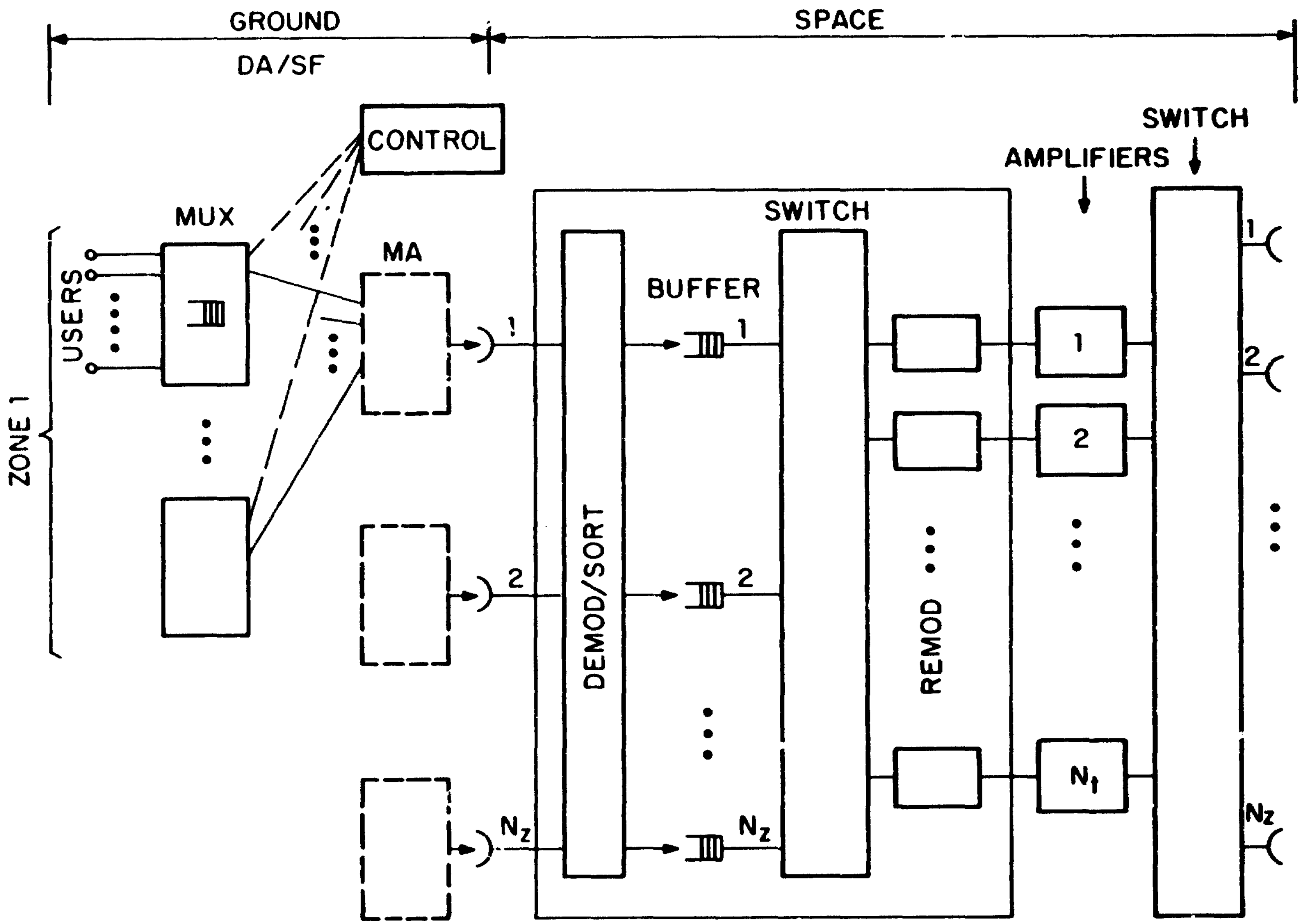
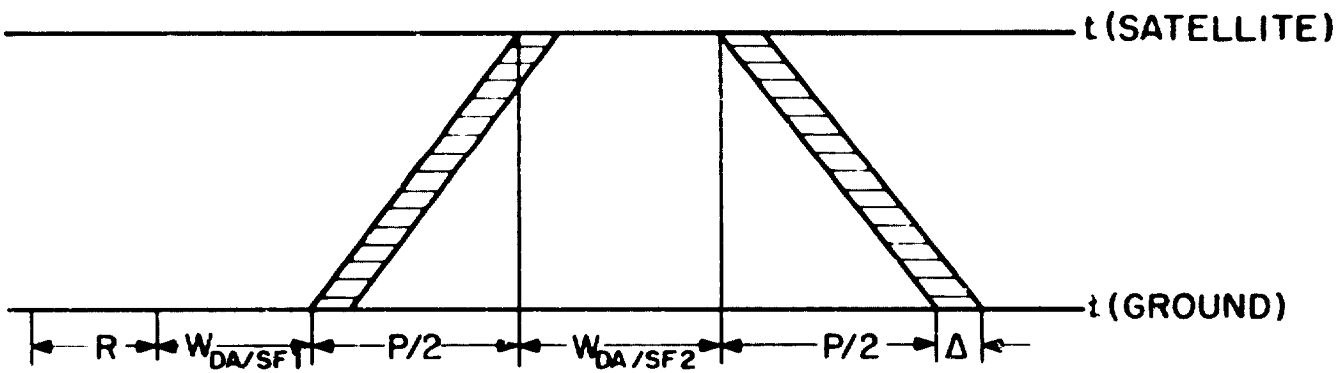


FIG. 2.16 DA/SF SYSTEM



$$\overline{T} = R + \overline{W}_{DA/SF1} + \overline{W}_{DA/SF2} + P + \Delta$$

FIG. 2.17 TIMING DIAGRAM (DA/SF)

CHAPTER 3

DELAY STUDIES OF FS SYSTEMS

In the last chapter, system configurations were described that are suitable for satellite switched multiple beam systems operating in a packet switched mode. We now begin delay studies of these systems. In this chapter, we focus attention on the FS systems. The DS and SF systems will be considered in Chapters 4 and 5, respectively.

A DA/FS system is considered first, in which a fraction of the total slots per frame are used as the order wire. We assume the general case where traffic between any pair of source-destination zones may have more than one slot allocated to it per frame, presenting analytic expressions for calculating average packet delays in the system. The delay expression for the case where each source-destination zone pair is allocated one slot per frame is obtained as a special case of these results. This analysis can be used for the FA/FS system as well since it has a similar frame structure. Finally, we present a delay analysis of RA/FS systems.

3.1 DA/FS AND FA/FS SYSTEMS

3.1.1 DA/FS SYSTEMS

We begin by considering the DA/FS system, illustrated in Fig. 3.1 for the case $N_Z = N_T$. We note here that for the case $N_T < N_Z$, the frame structure (as seen from Fig.2.5a) is similar except that the frame size [illegible] by the factor N_z/N_T. Thus, all of the analysis to follow is applicable for $N_T < N_Z$. In the DA/FS system illustrated in Fig. 3.1, a frame W slots long is established in which V slots are set aside for transmission of access control information while the remaining $(W - V)$ slots are used for data transmission. Each of the V control slots is sub-

divided into mini-slots, the length of a mini-slot being enough to carry one request message. A distributed control is assumed, and to facilitate such control, switchings for the control slots are arranged such that all transmissions are broadcast back to the transmitting zones. Access to the mini-slots is assumed to be on a fixed basis.

The protocol for this system is as follows. Upon receiving a message (i.e., a packet or a group of packets), a station sends a reservation request for this message in the next group of mini-slots. Thus, each group of mini-slots carries reservation requests for all packets arriving in the previous frame. All stations hear requests originating in their zone and each station forms N_Z queues of pending requests from all stations in its zone, one queue corresponding to each of the destination zones. Scheduling of packets is done on the basis of a predetermined rule, which we assume to be first-in first-out (FIFO). Consequently, all stations know when their packets are scheduled for transmission and no conflict can arise.

To analyze this system, we focus on the behavior of one of the queues, say the queue for transmissions from zone i to zone j. The transmission frame for this queue is shown in Fig. 3.1a. There are K slots per frame allocated for this traffic. The behavior of this queue is quite similar to the queue in Roberts' scheme [ROB 73], except that in our case the request slots always occur at fixed intervals whereas in Roberts' scheme the entire channel is converted into request slots when there are no packets scheduled for transmission. The behavior of the queue is modeled as an M/G/1 queue by Roberts, but with our fixed request slots, an M/G/1 model is a poor one and so, we obtain an exact expression for the expected number of requests in the queue at discrete times just

prior to the beginning of data slots in a frame. The analysis presented in Appendix A leads to the following expression for the expected request queue length $\bar{Q}$.

$$\bar{Q} = \tfrac{1}{2}\frac{\sigma^2_{i,j}}{K-\lambda_{i,j}} + \tfrac{1}{2}\lambda_{i,j} + \tfrac{1}{2}\sum_{t=2}^{K}\frac{1+\theta_t}{1-\theta_t} \qquad (3.1)$$

where

θ_t = The K zeroes of the equation $z^K - wP(z) = 0$ in the contour $|z| < 1$ and $|w| < 1$ and as $w \to 1$ from below. The zeroes are numbered such that $\theta_1 = 1$.

$P(z)$ = The generating function of the packet arrival process.

$\lambda_{i,j}$ = Average number of packets arriving in a frame for transmission from zone i to zone j.

$\sigma^2_{i,j}$ = Variance of the packet arrival process

We note here that $\sigma^2_{i,j}$ is a function of message length statistics. For the single packet, σ^2 (dropping the subscripts for convenience) is simply equal to λ. For the multipacket case, the average message length is 4.5 packets (see Sec. 2.1) and for an average packet arrival rate of λ, we have a message arrival rate of $\lambda/4.5$. This arrival process can be seen as the sum of two independent Poisson processes corresponding to the two classes of messages (single-packet or eight-packet) with a message rate of $\lambda/9$ for each. Then, the variance of the combined process is obtained as the sum of the variances of the two processes, so that the variance for the multipacket case is given by

$$\sigma^2 = \frac{\lambda}{9} + \frac{64\lambda}{9} \qquad (3.2)$$

$$= 7.22\,\lambda\,.$$

The average waiting time for requests $\overline{W}_{DA/FS}$ is determined from $\overline{Q}$ as in Eq.(A.13) of Appensix A.

Now consider the special case where every source-destination zone pair is allocated one slot per frame. An expression for $\overline{Q}$ is obtained for this case by using the previous analysis with $K = 1$, yielding

$$\overline{Q} = \tfrac{1}{2}\frac{\sigma^2_{i,j}}{1 - \lambda_{i,j}} + \tfrac{1}{2}\lambda_{i,j} \tag{3.3}$$

To obtain the waiting time $\overline{w}_{DA/FS}$ from $\overline{Q}$ in this case, we note that normally $\overline{W}_{DA/FS}$ (in units of frame period) could be calculated from the average request queue length using Little's formula [KLE 75b]. However, the $\overline{Q}$ obtained in this analysis applies only to the situation at the beginning of each frame; it is not the average over the entire frame. Nevertheless, by adjusting for the 1/2 frame average delay difference, it can be deduced that the correct value for $\overline{W}_{DA/FS}$ is

$$\overline{W}_{DA/FS} = \frac{\overline{Q}}{\lambda_{i,j}} - \tfrac{1}{2} \text{ in units of frame time} \tag{3.4}$$

For the balanced traffic case where all source zone/destination zone traffics are equal, $\lambda_{i,j}$ is equal to ρ, the normalized throughput of the system (see symbol list). Then, we have

$$\overline{W}_{DA/FS} = \frac{\overline{Q}}{\rho} - \tfrac{1}{2} \text{ (frames)} \tag{3.5}$$

and, from (2,3) $\overline{T} = \overline{R} + (\frac{\overline{Q}}{\rho} - \tfrac{1}{2})\ F + P + \Delta$ (3.5a)

For the case of DA/FS systems in which a terrestrial control link is used the frame structure is similar to that shown in Fig. 3.1 except that the control slots are not required anymore. As a consequence the frame length is somewhat reduced. However, Eqs. (3.3) through (3.5) are valid for this case also.

3.1.2 FA/FS SYSTEMS

Now we consider the FA/FS system. In these systems, slot allocation is made on a station basis and so, the frame length is N_s times longer than the previous case. The frame structure however remains similar and Eqs. (3.3) and (3.4) are still valid where $\lambda_{i,j}$ and $\sigma^2_{i,j}$ are replaced by the values appropriate for station/destination zone arrivals. As before, Eq. (3.5) is valid for the balanced traffic case where all station/destination zone traffics are equal.

Fig. 3.2 shows $\overline{W}$ as a function of ρ obtained from Eq. (3.5) for both single and multipacket messages. Waiting times can be obtained from these curves for any given system parameters.

To obtain values of average packet delays $\overline{T}$ for the FA/FS system, we must substitute the waiting time expressions derived in this section into the appropriate expression for $\overline{T}$ from Chapter 2. To illustrate, the average packet delays in FA/FS systems are found by substituting Eq. (3.5) into Eq. (2.2) to obtain

$$\overline{T} = \left(\frac{\overline{Q}}{\rho} - \tfrac{1}{2}\right) F + P + \Delta \quad \text{sec.} \tag{3.6}$$

where

$$\overline{Q} = \tfrac{1}{2}\,\frac{\sigma^2}{1-\rho} + \tfrac{1}{2}\rho \ . \tag{3.7}$$

3.1.3 ILLUSTRATION OF AVERAGE PACKET DELAYS

We now consider a specific example to illustrate the use of the above results for calculating average packet delay. Let $C = 2$Mbps, $N_z = 20$, $N = 40$, and packet length $L = 2000$ bits. This gives $\Delta = L/C = 1$ msec . Values of $\overline{T}$ are calculated for the following systems (balanced traffic is assumed throughout):

i) FA/FS: Here the frame length is $N_z \times N_s \times \Delta = 800$ msec

ii) DA/FS with terrestrial control: the frame length for this case

ρ	$\bar{T}$ (sec)		
	FA/FS	DA/FS (Terrestrial Control)	DA/FS (Satellite Control)
.2	3.47	.35	.64
.4	5.07	.39	.71
.6	7.47	.45	.8
.8	14.75	.63	2.58
.9	29.07	.99	--

Table 3.2. Average packet delays. Multipacket Arrivals.

is $\Delta \times N_z$ = 20 msec

iii) DA/FS with control via satellite order wire: We assume the structure of Fig. 3.1. A 200 bit reservation slot is sufficient giving 10 mini-slots per slot. For 40 stations, we need 4 slots per frame for the order wire. Assuming a frame 24 slots long, we have 20 data slots per frame with $K = 1$. The frame length is 24 msec .

The values of $\overline{T}$ for these three systems are listed in Tables 3.1 and 3.2 for various values of ρ for the single and multipacket cases. In the DA/FS system with satellite control, the channel saturates at $\rho = 20/24$.

ρ	$\overline{T}$ (sec)		
	FA/FS	DA/FS (Terrestrial Control)	DA/FS (Satellite Control)
.2	.75	.282	.55
.4	.93	.286	.56
.6	1.27	.295	.59
.8	2.27	.32	.85
9	4.27	.37	--

Table 3.1. Average packet delays. Single Packet Arrivals.

3.2 RA/FS SYSTEMS

The frame structure for an RA/FS system is similar to that for the DA/FS system, and, for the balanced traffic case assumed here, each source zone is allocated N_z slots per frame, one corresponding to each of the destination zones. The RA/FS system we consider is an extension of slotted Aloha. However, the multiple beam configuration of our system introduces the following complication in the random access scheme.

In our system, a station can hear its transmissions only when transmitting to other stations within its zone. Thus, for the most part, stations cannot hear their transmissions and in order to detect a collision, must wait for a positive acknowledgement. In the following analysis, we assume that a dedicated channel is available for sending acknowledgements and so, a station can detect a collision after 2P/F frames (twice the propagation time). We note that if the acknowledgements are sent piggybacked on data packets, we would also have to consider delays associated with sending acknowledgements. While collisions in transmissions to the same zone can be detected after P/F frames, this constitutes a small fraction of total traffic in systems with reasonably large N_z, so that for all practical purposes we may assume collisions are detected after 2P/F frames.

Since we are primarily interested in systems with high throughput, and since the random access schemes are known to have low throughput, the analytic results derived here for the RA/FS scheme are presented mainly for purposes of comparison. For the analysis, we focus on the traffic from zone i to zone j. All results derived for the slotted Aloha scheme can be used here with minor modifications. We take the approach of Klein-

rock and Lam [KLE 73] in which an infinite population model is used, noting that this approach does not take into account the inherent instability of the channel. In fact, Kleinrock and Lam [KLE 75] have shown that results obtained for such a model are valid only for a finite period of time after which the channel becomes saturated. However, they show that the results for a stable channel using a finite population model are closely approximated by those obtained by using the infinite population model. Therefore, we assume that the following results will accurately represent a situation with large but finite N_s and a stable channel. This analysis is valid only for the single packet case.

We define the following parameters for transmissions from zone i to zone j.

- S = Average of new packet arrivals per frame
- G = Average channel traffic in packets/frame. This includes newly generated packets as well as retransmitted packets.
- P/F = Round trip propagation delay in frames.
- k = Parameter defining retransmission strategy. A collided packet is randomly retransmitted equiprobably in one of the next k frames.
- q = Probability that the transmission of a newly generated packet is successful.
- q_t = Probability that the retransmission transmission of a collided packet is successful.

The relationship between S and G is given by the following equations [KLE 75]:

$$S = G \frac{q_t}{q_t + 1 - q} \tag{3.8}$$

$$q = \left[e^{-G/k} + \frac{G}{k}e^{-G}\right]^{k} e^{-S} \tag{3.9}$$

and

$$q_t = \left[\frac{1}{1 - e^{-G}}\right]\left[e^{-G/k} - e^{-G}\right]\left[e^{-G/k} + \frac{G}{k}e^{-G}\right]^{k-1} e^{-S} \tag{3.10}$$

Average packet delay in frames is given by

$$\overline{T} = \frac{1-q}{q_t}\left[\frac{2P}{F} + \frac{\Delta}{F} + \frac{k-1}{2}\right] + \frac{P}{F} + \frac{\Delta}{F} \tag{3.11}$$

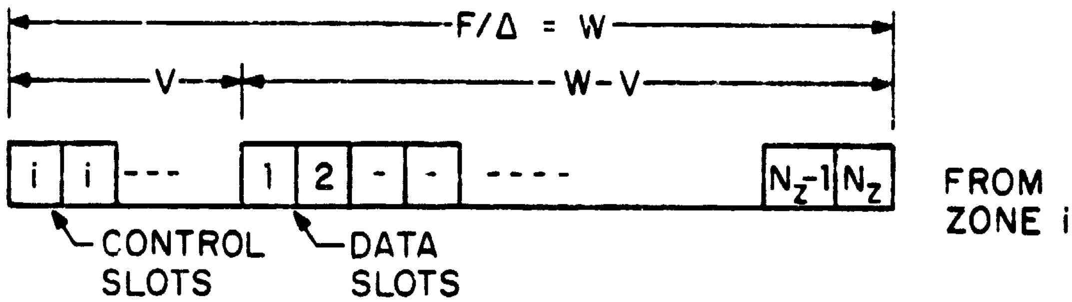
Equations (3.8),(3.9), and (3.10) must be solved simultaneously to find values of G, q, and q_t corresponding to various values of S. Using these in Eq. (3.11), values of $\overline{T}$ can be obtained.

We do this for the example of the previous section and list the values of $\overline{T}$ for the RA/FS system in Table 3.3. Note that the channel saturates at $\rho = 1/e \approx .37$.

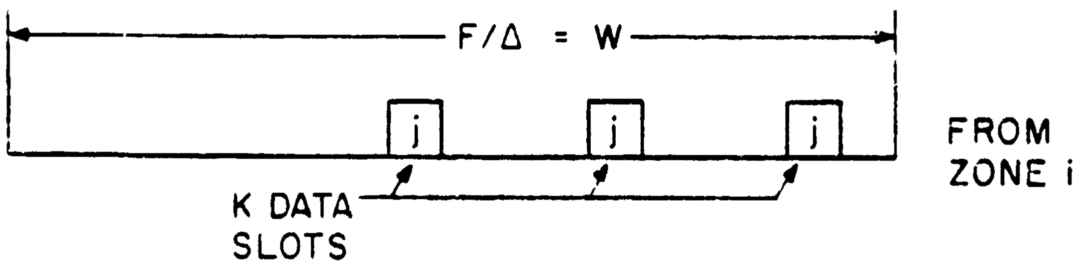
ρ	$\overline{T}$ (sec)
.1	.37
.2	.49
.3	.78
.35	1.12

Table 3.3. Average packet delays in RA/FS system. Single Packet Arrivals.

For these calculations, we have used a value of $k = 15$. Optimization of system performance as a function of k is discussed in [KLE 75], and from that discussion, $k = 15$ appears to be an appropriate choice for our system.



(a) FRAME FOR ALL TRANSMISSIONS FROM ZONE i



(b) TRANSMISSIONS FROM ZONE i TO ZONE j

FIG. 3.1 FRAME STRUCTURE FOR DA/FS SYSTEM

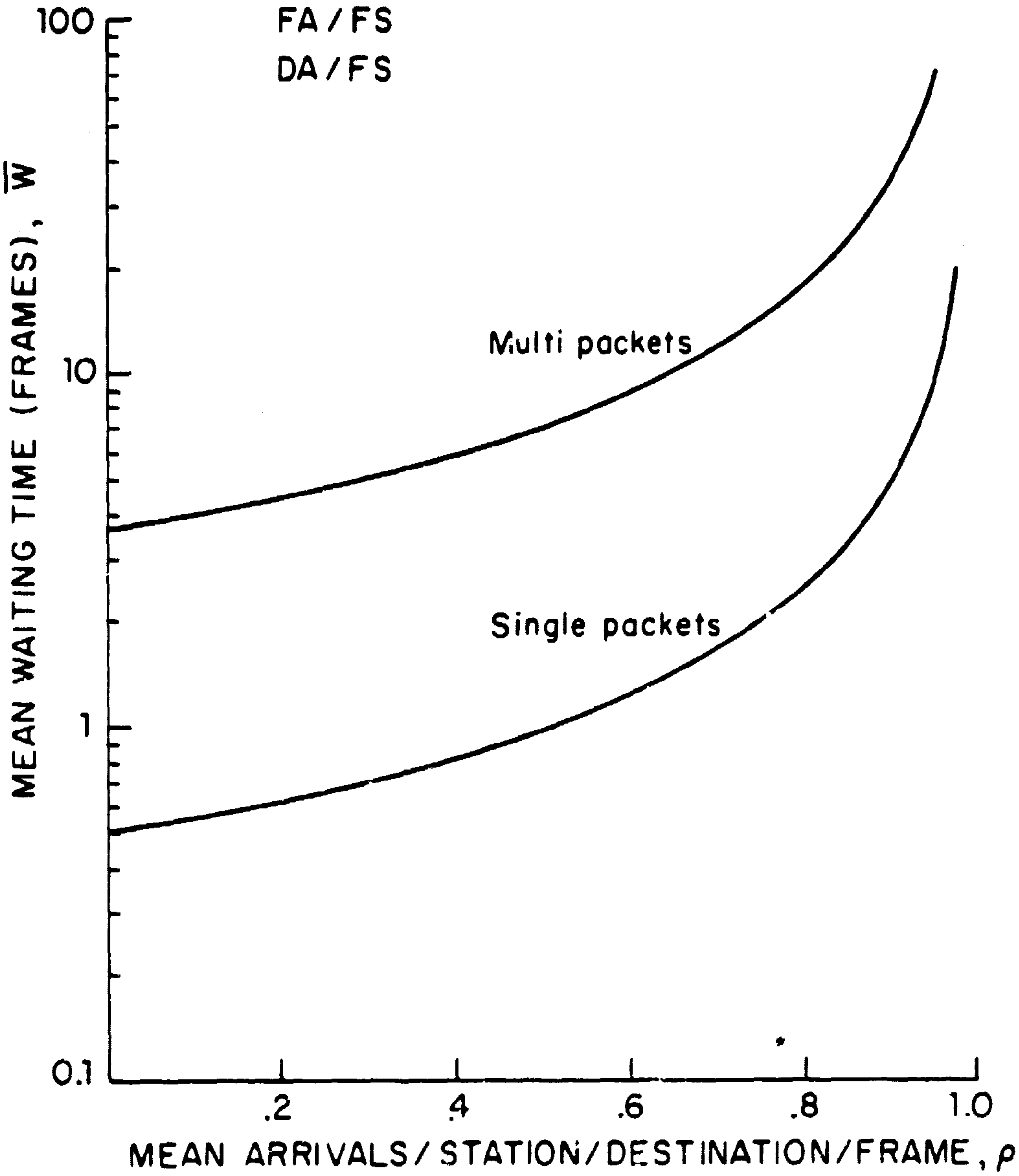


FIG. 3.2 WAITING TIMES IN FA/FS AND DA/FS SYSTEMS

CHAPTER 4

DELAY STUDIES OF DA/DS SYSTEMS

We now study packet delays in DS systems, where the switch assignments are made on demand on a slot-by-slot basis. The basic configuration of these systems was described in Chapter 2 and as mentioned there, we will only consider demand station access (DA) for the DS systems.

In a DS system, every station sends a request message to the controller for each arriving data packet. This message is a request for slot allocation for the data and includes information about the desired uplink-downlink connection. Based on a list of all pending requests, the controller makes switch assignments for each slot. The switch assignments must be made subject to the switching constraints which state that any one uplink zone may not be connected to more than one downlink zone at the same time. Similarly, any one downlink zone may not be connected to more than one uplink zone. Also, the total number of connections at any given time cannot exceed the number of transponders N_T. We wish to find efficient algorithms that can be used by the controller to make switch assignments. An efficient algorithm is one which is simple to implement and which also reduces request waiting times. We begin this chapter by describing the scheduling process and presenting some switch scheduling algorithms.

Next, simulation results are presented for the calculation of average waiting time, $\overline{W}_{DA/DS}$, for these algorithms at various values of system parameters. When these algorithms are used for request scheduling, the resulting queueing process becomes very complicated and difficult to analyze. Therefore, we resort to simulation to obtain preliminary

results comparing the performance of the algorithms. One of the algorithms, called List Scheduling appears to be the most promising, and for it we give analytical results for the calculation of $\overline{W}_{DA/DS}$, based on some Markov models. Finally, we compare the analytic results with the results of simulations and discuss the validity of the mathematical models.

4.1 SWITCH SCHEDULING ALGORITHMS

The controller forms a queue of all pending requests and, on the basis of the information in the queue and a particular scheduling algorithm, schedules switch positions on a slot-by-slot basis. The scheduling process and the switching constraints are illustrated in the following example.

We consider a system in which $N_z = N_T = 5$. The contents of the queue of all pending requests at the controller is shown in Fig. 4.1 in a matrix form. Each cell in the matrix corresponds to a pair of source and destination zones, and an entry in the cell indicates a request for a packet transmission between those zones. The total number of entries in the matrix indicates the length of the request queue and the entry number indicates the position of the request in the queue. The switching constraints require that no more than one entry can be scheduled in a given time slot from the same row or column of the matrix.

In the following sections, we present three switch scheduling algorithms and present performance curves for these algorithms in later sections.

4.1.1 MAXIMUM MATCHING SCHEDULING

If the purpose of the scheduling algorithm is to minimize average waiting time in the request queue, then clearly, the algorithm must schedule a maximum number of requests in each slot while also satisfying the switching constraints. We define the schedule that does this as the maximum matching schedule.

The example of Fig. 4.1 will be used to illustrate this schedule. The scheduler must make a switch assignment for the next available slot based on the indicated request queue. The problem of scheduling the maximum number of requests for this example is shown in Fig. 4.2, where the contents of the queue are shown in the form of a bipartite graph. The vertices on the left of the graph correspond to source zones while those on the right correspond to destination zones. The edge connecting any two vertices represents a request in the queue for the appropriate source-destination pair. Note that the case where are more than one request for any source-destination pair is represented by one edge as it does not alter the scheduling procedure. In such a case, we assume that the scheduling for this source destination pair is done using a FIFO (first-in, first-out) rule.

It is evident that an allowable schedule is represented by a matching, which is defined as a subset of edges such that no two edges are incident on the same node. Thus, the problem of scheduling a maximum number of requests is equivalent to finding a maximum matching in the bipartite graph. This is a well known problem in graph theory and a number of algorithms have been proposed to solve it. The most efficient algorithm [HOP 73] requires $\sim n^{5/2}$ operations to find a maximum matching in a graph with n vertices. Thus, to implement this scheduling algorithm

for a system with N_z zones, the scheduler will be required to perform $\sim (2\ N_z)^{5/2}$ operations per slot. For our example, the maximum matching schedule can be found by inspection. This, along with the schedules for some other algorithms is shown in Fig. 4.3. Requests 3,5,4,6 and 8 are scheduled resulting in full utilization of all five transponders. We note that this may not always be possible. Also, a number of maximum matchings may be possible for some cases. For these cases, we assume that one of these matching is chosen by a predetermined rule. For the simulation study of this algorithm, one of these matchings is chosen in an arbitrarily determined priority order.

4.1.2 SCHEDULING USING CYCLIC PERMUTATIONS

The average waiting time in the request queue is minimized by the maximum matching scheme. However, as indicated above, to implement this scheme the scheduler must solve a complex combinatorial problem requiring $\sim (2\ N_z)^{5/2}$ operations, once every slot. For a system with large N_z, this would put a prohibitive computational burden on the scheduler and so, we consider next two sub-optimal schemes. In this section an algorithm based on a subset of possible switch positions is discussed. Section 4.1.3 describes a first-come first-served strategy.

The allowable assignment for a system with $N_z(=N_T)$ zones can be one of $N_z!$ switch states. Instead of considering all of these states, we only consider a small subset corresponding to the set of cyclic permutations. The allowable connections for the example of a 5-zone system are shown in Table 4.1.

Table 4.1 Possible Cyclic Connections

Source-Destination ↓ \ Connection →	1	2	3	4	5
	1-1	1-2	1-3	1-4	1-5
	2-2	2-3	2-4	2-5	2-1
	3-3	3-4	3-5	3-1	3-2
	4-4	4-5	4-1	4-2	4-3
	5-5	5-1	5-2	5-3	5-4

For the example of Fig. 4.1 , the best schedule can be found by inspection and it is seen that either connection 1 or 2 can be chosen. Arbitrarily choosing connection 1 , we see that requests 1,2 and 8 are scheduled which is clearly not the optimum. This schedule is illustrated in Fig. 4.3c.

4.1.3 LIST SCHEDULING

This is another sub-optimal scheme in which the scheduler simply scans the list of requests in the queue and schedules them if consistent with switching constraints. The scanning of requests is done on a first-come-first-served basis and terminates if either N_T requests have been scheduled or if all requests have been scanned.

For the example of Fig. 4.1, a list scheduling strategy would result in the scheduling of requests 1,2 and 8 as shown in Fig. 4.3d.

4.2 SIMULATIONS OF SCHEDULING SCHEMES

In this section, we present results of simulations performed to calculate average packet waiting time $\overline{W}_{DA/DS}$, of requests in the scheduler request queue for the three algorithms. For simulations, we consider the

case $N_z = N_T = 5$. We assume that message arrivals at various stations destined for various zones form independent Poisson processes. We also assume a balanced traffic case. For our waiting time studies, we consider two cases of message lengths. The single packet case where every message consists of a single packet and the multi-packet case where a message consists either of a single packet or a block of eight packets with equal probability.

The simulations were performed in GPSS for various values of traffic intensity, ρ. Confidence intervals for the simulation results were computed for selected values of ρ and they were all well within $\pm$ 5%. The confidence intervals were calculated using the method of batch means. Since multiple access considerations are the focus of this present report, technology dependent estimates of computation time in setting up connections are not included in the simulation results.

The value of average waiting time $\overline{W}_{DA/DS}$ for the maximum matching scheme is given for various values of ρ and for the two cases of message lengths in Table 4.2. The results for the two sub-optimal schemes are given in Tables 4.3 and 4.4. Although scheduling is done on a packet-by-packet basis, there is no extra waiting time at originating ground stations for multipacket messages because requests are sent to the schedule in blocks.

In order to make a comparative evaluation of the three scheduling schemes based on these results for the case $N_z = N_T = 5$, curves of $\overline{W}_{DA/DS}$ (measured in slots) are plotted as a function of ρ in Figures 4.4 and 4.5 for single and multipacket cases respectively. For both cases the maximum matching scheme, as expected, has the minimum waiting times. The sub-optimal scheduling that uses cyclic permutations reduces the computational requirements of the system but the resulting waiting times are very high. The list scheduling scheme is superior in performance to cyclic permutation and is not too far from maximum matching over a wide

range of ρ. Since list processing combines high performance with superior computational efficiency, we will focus attention on the list scheduling algorithm in the analysis that follows. Maximum matching will be abandoned because of its computation complexity, and cyclic permutations will be discarded because of its poor performance.

Table 4.2 Maximum matching Schedule:

$N_T = N_z = 5$

(a) Single Packet Arrivals

Traffic Intensity ρ	Average Waiting Time $\overline{W}_{DA/DS}$ (slots)
.403	1.05
.618	1.89
.816	4.46
.93	11.5

(b) Multi-packet Arrivals

Traffic Intensity ρ	Average Waiting Time $\overline{W}_{DA/DS}$ (slots)
.199	5.32
.405	8.47
.605	12.1
.814	29.6

Table 4.3 Scheduling Using Cyclic Permutations

$N_T = N_z = 5$

(a) Single Packet Arrivals

Traffic Intensity ρ	Average Waiting Time $\overline{W}_{DA/DS}$ (slots)
.198	.25
.407	2.89
.616	5.41
.813	11.6
.924	40.2

(b) Multi-packet Arrivals

Traffic Intensity ρ	Average Waiting Time $\overline{W}_{DA/DS}$ (slots)
.198	10.1
.404	20.7
.601	34.7
.811	69.9
.892	124.9

Table 4.4 List Scheduling $N_T = N_z = 5$

(a) Single Packet Arrivals

Traffic Intensity ρ	Average Waiting Time $\overline{W}_{DA/DS}$ (slots)
.202	.627
.403	1.08
.617	2.21
.815	6.11

(b) Multi-packet Arrivals

Traffic Intensity ρ	Average Waiting Time $\overline{W}_{DA/Ds}$ (slots)
.190	5.11
.387	8.1
.596	14.04
.787	30.4

4.3 WAITING TIME ANALYSIS OF SCHEDULING ALGORITHMS

For mathematical analysis of these scheduling algorithms, we must distinguish between N_z^2 different classes of packets corresponding to the N_z^2 inter zone traffics. The pending requests may therefore be modeled as N_z^2 queues contending for N_T servers. The switching constraints and scheduling algorithms introduce complex coupling among the queues and as a result, an exact mathematical analysis appears to be out of the question. Our system appears to be similar to the widely studied problem of a two stage link system in telephone networks [ELL 56]. However, we have not been able to extend those results to our study because of the discrete nature of these systems and the unique scheduling rules. We have, however, developed some approximate models which are the subject of the remainder of this chapter. In this section we give a loose lower bound for the waiting time in the maximum matching schedule, and in the next section we will present a detailed analysis of the list scheduling algorithm using Markov models.

To lower bound $\overline{W}_{DA/DS}$, for the case $N_z = N_T$, we note that in any given slot, the number of requests that are allocated cannot exceed N_z. However, even when the number of requests in the queue is larger than N_z, it is not always possible to schedule N_z requests. A lower bound is obtained if we focus on requests originating from any one zone and ignore the switch constraints. Thus, to obtain a lower bound on $\overline{W}_{DA/DS}$ using the maximum matching algorithm, we may model it using N_z separate single server queues. For the analysis of this system, we note that since we are assuming balanced traffic, the behavior of each of the N_z queues is identical. The analysis is similar to that presented for the DA/FS system where frame length is equal to one slot.

This lower bound is compared with simulation results for the five zone maximum matching algorithm in Fig. 4.6 and 4.7. Although the lower bounds are relatively loose, they can still be used for comparison purposes in systems with large number of zones where simulation of an exact model would be very time consuming.

4.4 MARKOV MODELS FOR LIST SCHEDULING

We now present some analytic results based on Markovian models of the list scheduling algorithm. We model the request queue as a single queue of all requests awaiting scheduling, with bulk service at discrete intervals of time. The number of requests scheduled in any time slot is a discrete variable taking integer values from 0 to N_T. This variable is a function of the state of the request queue, defined by the identities (source-destination labels) and positions of all requests in the queue. Since such a state description is far too complex to deal with in any exact analysis, we shall make the following simplifying "independence assumptions", which vastly reduce the size of the state space and make the resultant model tractable.

i) Each new request falls independently and equiprobably into each source-destination cell and

ii) Items on the list are assumed to take on new random identities independently and equiprobably, each time the list is scanned.

The first assumption is accurate for the case of single packet arrivals and balanced traffic. However, the second assumption, implying that the system loses all memory of its exact state from one time slot to the next, is a source of certain inaccuracies in our results.

Based on the independence assumptions, the state of the system can now be defined simply as the <u>length</u> of the request queue. The relation between packets scheduled and pending requests is then derived as follows. Let $d_{\ell/m}$ be the probability that ℓ requests are scheduled given that these are m requests on the list. Then, the following properties of $d_{\ell/m}$ are obvious

$$\begin{aligned} d_{0/m} &= 1 \qquad \text{if} \quad m = 0 \\ &= 0 \qquad \text{otherwise} \\ d_{1/1} &= 1 \end{aligned} \tag{4.1}$$

and $\quad d_{\ell/m} = 0 \qquad \text{for} \quad \ell > m$

From our assumptions, we note that

$$d_{1/m} = (1 - \alpha_1)\, d_{1/m-1} \qquad m = 2,3,\ \ldots \tag{4.2}$$

and

$$d_{\ell/m} = (1 - \alpha_\ell)\, d_{\ell/m-1} + \alpha_{\ell-1}\, d_{\ell-1/m-1}$$

$$\text{for} \quad \ell = 2,3,\ldots N_T \text{ and } m = 2,3,\ldots \tag{4.3}$$

where

$$\alpha_\ell = (1 - \frac{\ell}{N_z})^2 \tag{4.4}$$

Based on these equations we develop two types of Markovian models described in the following two sections. The first is a discrete time Markov chain and appears to be a fairly accurate representation of the behavior of the algorithm, but is rather difficult to analyze. The second is a continuous time birth-death model which is analytically simpler but at some cost in accuracy. Each model is used to obtain ergodic probabilities for the state of the request list, from which average request waiting time is found .

4.4.1 DISCRETE TIME MARKOV CHAIN

We model the contents of the request list as a discrete time Markov chain using the following definitions:

$M(k)$ = Number of requests in the list just prior to the beginning of the k^{th} slot.

$L(k)$ = Number of requests scheduled in the k^{th} slot.

$N(k)$ = Number of new requests received during the k^{th} slot.

$P_m(k)$ = Prob. $[M(k) = m]$

a_n = Prob $[N = n]$

$$= \frac{\lambda^n e^{-\lambda}}{n!} \quad \text{for the single packet arrival case} \tag{4.5}$$

where λ = arrival rate, packets/slot.

For the multipacket case, the values of a_n are a little more complex. The average message length is 4.5 (see Sect. 2.1), and for an average packet arrival rate of λ, we have a message arrival rate of $\lambda/4.5$. We can look at the arrival process as two independent Poisson processes (corresponding to the two classes of messages) with a message arrival rate of $\lambda/9$ for each process. Then, for the two processes, we get the following values of a_{n_1}

$$a_{n_1} = \frac{(\lambda/9)^n \, \ell^{-(\lambda/9)}}{n!} \qquad n = 0,1,2,\ldots \tag{4.6}$$

$$a_{n_8} = \frac{(\lambda/9)^{n/8} \, \ell^{-(\lambda/9)}}{n!} \qquad n = 0,8,16,\ldots \tag{4.7}$$

where a_{n_1} = Prob $[N = n]$ for single packet messages

and a_{n_8} = Prob $[N = n]$ for multi packet messages

From the above, values of a_n for the combined arrival process can be obtained. The system evolves according to the following equation

$$M(k+1) = M(k) - L(k) + N(k) \tag{4.8}$$

Using equations (4.2) and (4.3) together with equation (4.8), we have

$$P_m(k+1) = \sum_{\ell=0}^{N_T} \sum_{n=0}^{m} P_{m+\ell-n}(k)\, d_{\ell/m+\ell-n}\, a_n \tag{4.9}$$

The Markov chain is ergodic if the following condition is met (for the balanced traffic case)

$$\sum_i \sum_j \lambda_{ij} = \lambda < N_T \tag{4.10}$$

where λ_{ij} = Arrival rate (packets/slot) for traffic from source zone i to destination zone j.

This is because $d_{NT}/m \to 1$ as m becomes large, and if $\lambda < N_T$, the arrival rate in the system is smaller than the service rate . We denote the limiting distribution of the random variable M(k) as $k \to \infty$, by P_m, which must satisfy

$$P_m = \sum_{\ell=0}^{N_T} \sum_{n=0}^{m} {}_{m+\ell-n}\, d_{\ell/m+\ell-n}\, a_n \tag{4.11}$$

Eq. (4.11) represents an infinite set of equations which can, in principle, be solved for the limiting distribution p_m; unfortunately, we have been unable to obtain a closed form solution of these equations. However, an approximate solution can be obtained by setting a finite upper limit m_{max} on the value of m, and solving the resulting simultaneous

equations together with the normalizing equation

$$\sum_{m=0}^{m_{max}} P_m = 1 \tag{4.12}$$

This 'approximation' actually yields a more realistic solution than the case $m_{max} = \infty$ since any real system will necessarily have a finite buffer size.

From these values of P_m, the average length $\bar{Q}_M$ of requests in the list is obtained as

$$\bar{Q}_M = \sum_{m=0}^{m_{max}} m\, P_m \tag{4.13}$$

Average waiting time $\bar{W}_{DA/DS}$ can be found from $\bar{Q}_M$ as (see Sect. 3.1)

$$\bar{W}_{DA/DS} = (\bar{Q}_M/\lambda) - 1/2 \tag{4.14}$$

4.4.2 BIRTH-DEATH MODEL

In order to simplify the analysis still further, we now approximate the behavior of the request queue using a continuous time birth-death model with an arrival rate of λ requests/slot. The departure rate μ_m is a function of queue length m and is taken to be

$$\mu_m = \bar{L}_m = \sum_{\ell=1}^{N_T} \ell \; d_{\ell/m} \tag{4.15}$$

Where $\bar{L}_m$ is the expected number of departures per slot, conditioned on queue length m.

In other words, we are using a model with Poisson arrival rate of λ requests/slot and an exponentially distributed state dependent inter-departure time with mean $1/\mu_m$ slots. Note that the 'slot' is used here only as a convenient unit of time, requests being assumed to depart from the queue at random times. We wish to solve for $P_m(t)$ where

$P_m(t)$ = Prob. queue size is m at time t

A state diagram for this birth-death process is shown in Fig. 4.8. Transitions from any state E_m can occur only to the neighboring states E_{m-1} or E_{m+1}. Clearly, for any state E_m.

$$\text{Flow rate into } E_m = \lambda P_{m-1}(t) + \mu_{m+1} P_{m+1}(t) \tag{4.16}$$

and

$$\text{Flow rate out of } E_m = (\lambda + \mu_m) P_m(t) \tag{4.17}$$

Thus, the evolution of $P_m(t)$ is defined by the infinite set of differential equations

$$\frac{d\,P_m(t)}{dt} = \lambda\, P_{m-1}(t) + \mu_{m+1}\, P_{m+1}(t) - (\lambda + \mu_m)\, P_m(t) \qquad (4.18)$$

$$m = 0,1,2,\ldots$$

By applying the principle of local balance, we obtain the following set of equations describing the limiting probabilities P_m

$$P_{m+1} = \frac{\lambda}{\overline{L}_{m+1}}\, P_m \qquad m = 0,1,2,\ldots \qquad (4.19)$$

and $\sum_{m=0}^{\infty} P_m = 1$

The limiting distribution exists if

$$\lambda < N_T$$

because $\overline{L}_m \to N_T$ as $m \to \infty$

While the set of equations (4.19) is simpler than (4.11) a closed form solution could still not be found because of the complexity of the conditional probabilities $d_{\ell/m}$. An approximate solution for this set of equations was again found by choosing a large but finite value of m_{max}.

Tables 4.5 and 4.6 show waiting time-throughput results for the two analytic models along with corresponding values obtained from simulation for two cases $N_z = N_T = 5$ and $N_z = N_T = 10$ respectively. To facilitate comparison the results are plotted in Fig. 4.9 and 4.10. Single packet arrivals are assumed in all cases. (Our first assumption that arriving requests fall independently into all cells is clearly not valid for the multi-packet case)

Table 4.5 LIST SCHEDULING

$N_z = N_T = 5$

Traffic Intensity ρ	Mean waiting time		
	Simulation	Analytic Models	
		Discrete Markov Chain	Birth-Death
.202	1.62	1.734	1.274
.403	2.08	2.128	1.718
.617	3.21	2.975	2.654
.815	7.10	5.175	5.045

Table 4.6 LIST SCHEDULING

$N_z = N_T = 10$

Traffic Intensity ρ	Mean waiting time		
	Simulation	Analytic Models	
		Discrete Markov Chain	Birth-Death
.403	2.24	2.152	1.7
.614	3.5	3.026	2.62
.818	7.87	5.627	5.35

From these results, it is clear that the discrete time Markov chain model results agree quite well with those of simulation for values of ρ up to about .6 but for higher values of ρ, the average waiting times given by the model are smaller than the simulation results. Since the model is an accurate representation of the system except for the simplifying assumptions involved in the determination of the probabilities $d_{\ell/m}$, we have studied the validity of these assumptions in order to determine the source of the discrepancies between analysis and simulation.

In Table 4.7, we list values of $\overline{L}_m$ obtained from simulation together with those calculated from equations (4.2) and (4.3) for various values of m for a system with $N_z = N_T = 5$. The values of $\overline{L}_m$ from simulation were obtained at $\rho = .815$. (Values of $\overline{L}_m$ from simulation at other values of ρ do not show significant variations.)

Table 4.7 MEAN DEPARTURE RATE $\overline{L}_m$ vs. QUEUE LENGTH m

$N_z = N_T = 5$

m	$\overline{L}_m$ Simulation	$\overline{L}_m$ Analysis
2	1.66	1.64
5	2.67	2.728
10	3.38	3.546
15	3.63	3.956
20	3.98	4.205
25	4.11	4.375
30	4.24	4.5
40	4.35	4.659

From the table, it is clear that except for very low values of $\bar{L}_m(=2)$, the values of $\bar{L}_m$ observed from simulations of an exact model are significantly lower than those obtained by calculations using our simplifying assumptions. This means that the assumptions give an optimistic picture of the system; in reality, the average number of packets scheduled for transmission for a queue length m is less than that derived from equations (4.2) and (4.3). This behavior can be explained intuitively in the following way.

Consider the two contrasting cases of lists of pending requests shown in Fig. 4.11. In both cases, there are five requests in the list but the first is a favorable case where all requests can be scheduled whereas the second is an unfavorable case where only one request can be scheduled. When the scheduler scans the list for the next slot, it only finds newly arrived requests in the first case,and these fall equiprobably in all cells. In the second case, however, in addition to the newly arrived requests, it finds four 'leftover' requests which still constitute an unfavorable case. The leftovers are redistributed in the simplified model and this is what produces the 'optimistic' results.

The higher calculated values of $\bar{L}_m$ in the Markov model produce values of waiting time which are clearly lower in the analytic models than in the actual system. The system is more sensitive to this error in calculating $\bar{L}_m$ at higher values of ρ, and as a result, average waiting time determined from the analytic models differ more from those of simulation as the value of ρ goes beyond .6.

4.4.3 A SECOND ORDER CORRECTION

We now present a second order correction for the analytic results on average queue length $\bar{Q}_M$, obtained from the discrete time Markov model. (As will be explained later, this correction is only valid for the case $N_z = N_T$.) The delays in the analytic model are lower because of the lack of validity of the independence assumption. To understand how a correction may be made for the effect of this assumption, consider the following two queueing systems.

CASE I: An N-Queue, N-Server discrete time model:

This queueing model is shown in Fig. 4.12. We assume that there are N independent queues each served by a separate server and the service starts at discrete times. The analysis for this system is identical to that of the DA/FS system of Chapter 3 with the frame length equal to one slot. The average queue length of the system is the sum of average queue lengths of each of the queues, and for equal traffic, it is given by

$$\bar{Q}_E = N\left[\frac{1}{2}\,\frac{\sigma^2}{1-\rho} + \frac{1}{2}\,\rho\right] \tag{4.20}$$

CASE II:

We consider the system above and analyze it using our independence assumption. The service again starts at same discrete times for each of the N servers but at the beginning of each service period, we assume that all packets are redistributed in the N queues (cells) with equal probability.

This system can be analyzed in a manner similar to that used for the list scheduling. We can use equation (4.11) for this case also but with

different values for the conditional probabilities $d_{\ell/m}$. The $d_{\ell/m}$ for this case are

$$d_{1/1} = 1$$

$$d_{1/m} = \frac{1}{N} d_{1/m-1} \qquad m = 2,3,\ldots \qquad (4.21)$$

and

$$d_{\ell/m} = \frac{\ell}{N} d_{\ell/m-1} + \frac{N-(\ell-1)}{N} d_{\ell-1/m-1}$$

$$m = 2,3,\ldots$$

Again, we can solve for the expected queue length for a reasonably high m_{max}, defining this as $\overline{Q}_I$.

Since the nature of redistribution of queue contents here is similar to that occurring in our discrete Markov model, we use the ratio $\overline{Q}_E/\overline{Q}_I$ as a correction factor.

We choose N in Case I and II equal to N_z, the number of zones in the system. For each value of ρ, we calculate $\overline{Q}_I$, $\overline{Q}_E$ and $\overline{Q}_M$, the expected value of queue length using the discrete Markov model. From these, we find a corrected value $\overline{Q}_c$ of average queue length in a list scheduling system as

$$\overline{Q}_c = \frac{\overline{Q}_E}{\overline{Q}_I} \cdot \overline{Q}_M \qquad (4.22)$$

The corrected waiting time is derived from $\overline{Q}_c$ as explained in Sect. 3.1. Curves of corrected values of average waiting time are plotted as a function of traffic intensity ρ in Figures 4.13, 4.14 and 4.15 for single packet messages and for the three cases $N_z = N_T = 5$, $N_z = N_T = 10$ and $N_z = N_T = 20$. In these figures we also show simulation points and

average waiting time curves for the Markov chain model using the independence assumptions. It is clear that the corrected values agree very well with the simulations for all values of ρ. Next, we plot similar curves for the multipacket case in Fig. 4.16, 4.17 and 4.18. Even for the multipacket case, corrected values are in agreement with the simulations.

The case of $N_T < N_z$ is more complex. In order to obtain correction curves for this case, the model of Case I must be modified. We must consider a system with N_z queues and N_T servers and with some unique couplings among the queues. An exact expression for average queue length for this system is difficult to obtain. If we use a simpler model of either N_z-queue, N_z-server or N_T-queue systems, the corrected values do not agree with simulation. We therefore are limited to the use of simulation results for comparative evaluation of systems with $N_T < N_z$.

In conclusion, an example will be presented to illustrate the advantage of systems with $N_z > N_T$. In Fig. 4.19, average waiting time is plotted against throughput (packets/slot) for three system configurations each using a list scheduling algorithm. Two of these configurations employ equal numbers of transponders and zones. ($N_z = N_T = 5$ and $N_z = N_T = 10$). The third configuration has ten zones but only five transponders. Single packet arrivals are assumed throughout. The advantages of employing a larger number of zones than transponders are evident. The case $N_z = 10$, $N_T = 5$ has considerably lower waiting time than $N_z = N_T = 5$. The former system also has waiting times quite close to those for the system with $N_z = N_T = 10$ for values of throughput up to about 4.5 after which the system with fewer transponders quickly reaches saturation. Thus, if throughput is limited to less than 4.5 packets/slot, the system with

$N_z = 10$, $N_T = 5$ can be used without significantly increasing waiting time and at a considerable reduction in weight on board the satellite.

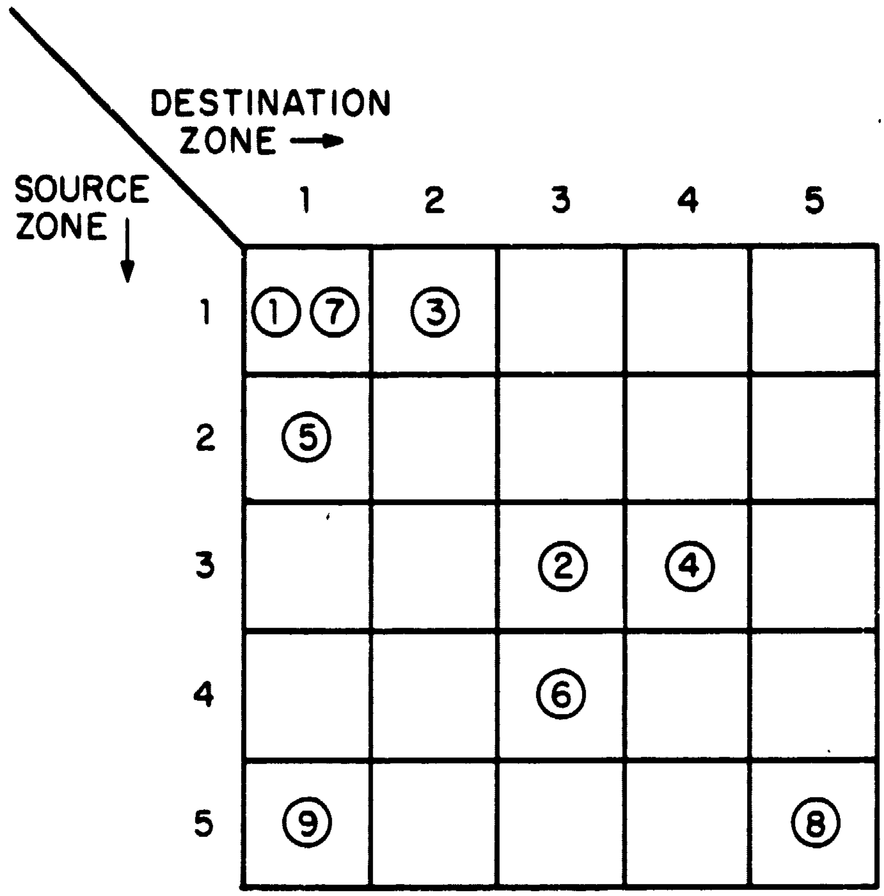


FIG. 4.1 CONTENTS OF THE REQUEST QUEUE:
ORDER OF REQUESTS RECEIVED SHOWN ENCIRCLED

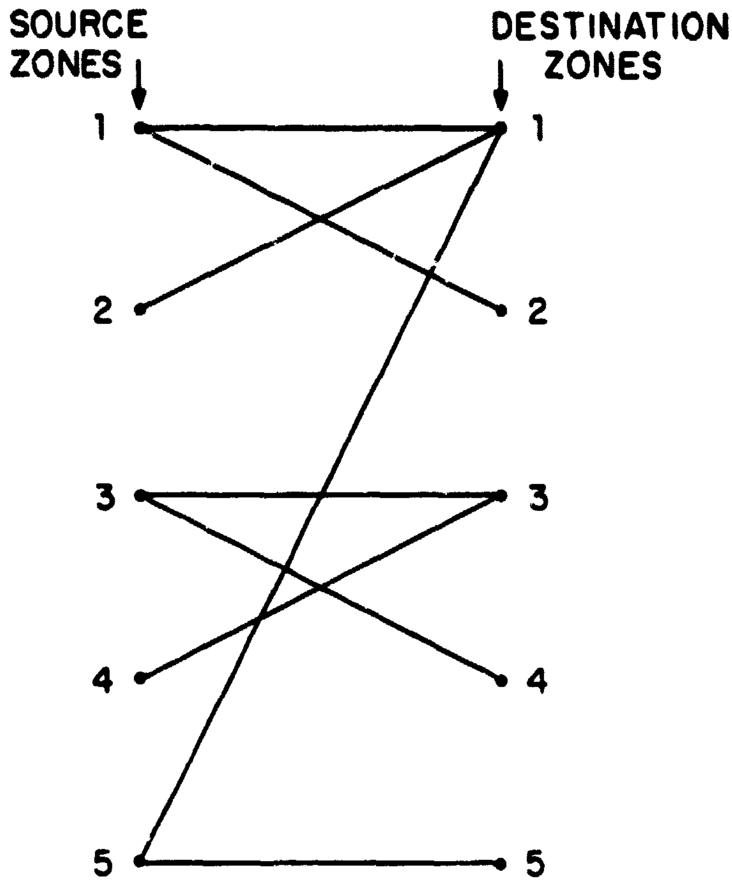


FIG. 4.2 BIPARTITE GRAPH REPRESENTING CONTENTS
OF REQUEST QUEUE

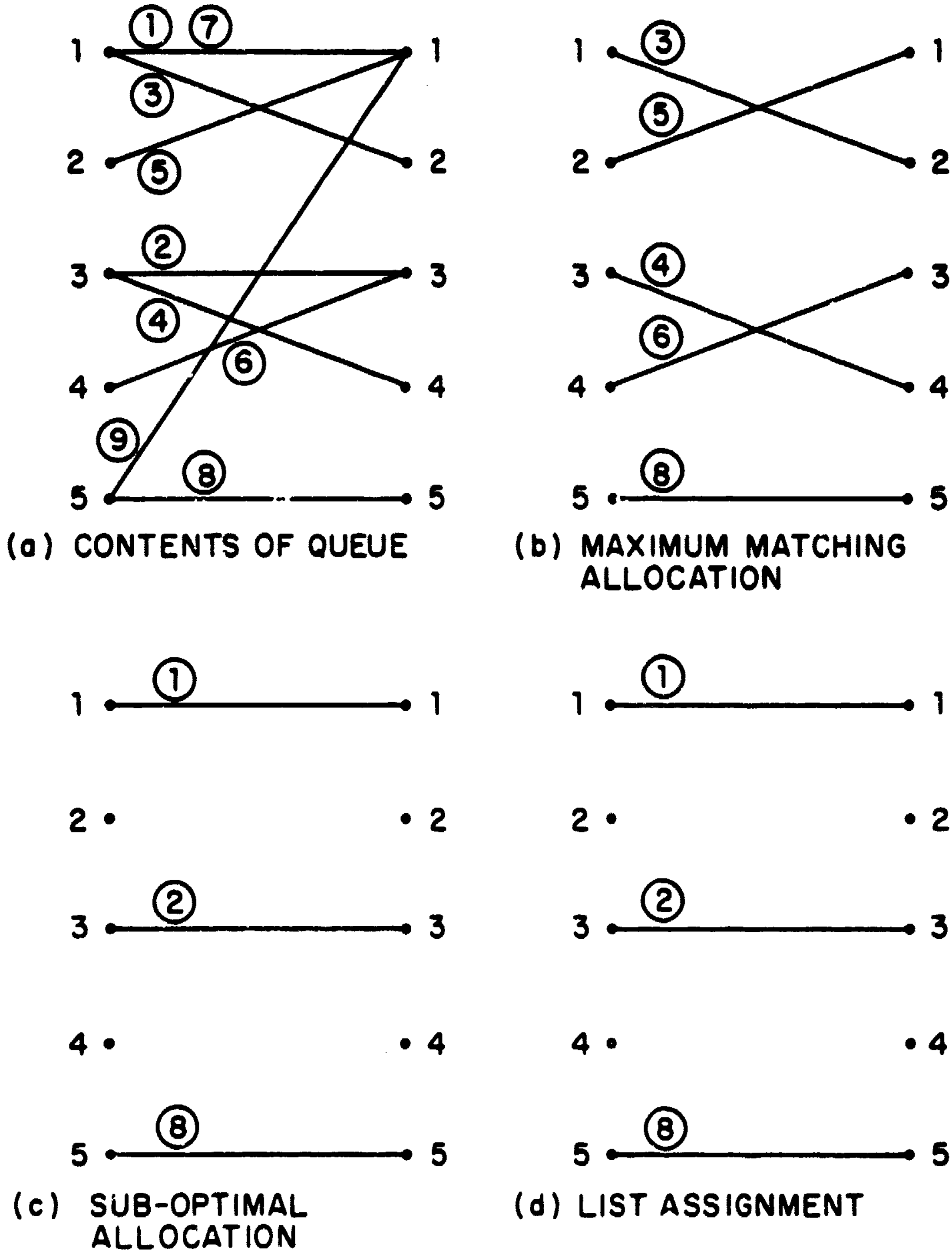


FIG. 4.3 ILLUSTRATION OF SCHEDULING ALGORITHMS

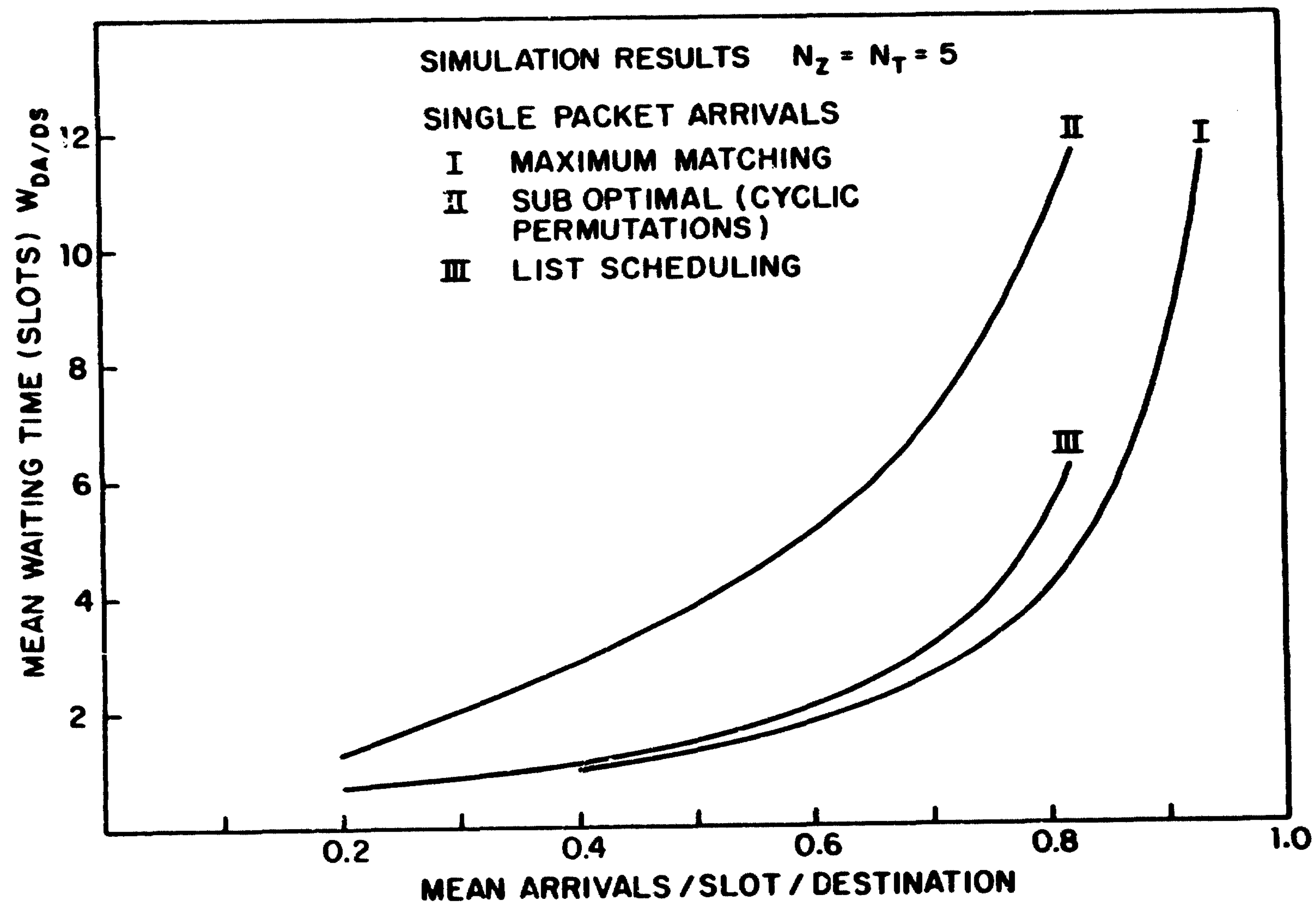


FIG. 4.4 WAITING TIME CURVES (DA/DS), SINGLE PACKETS

A-EE-2056 WL.

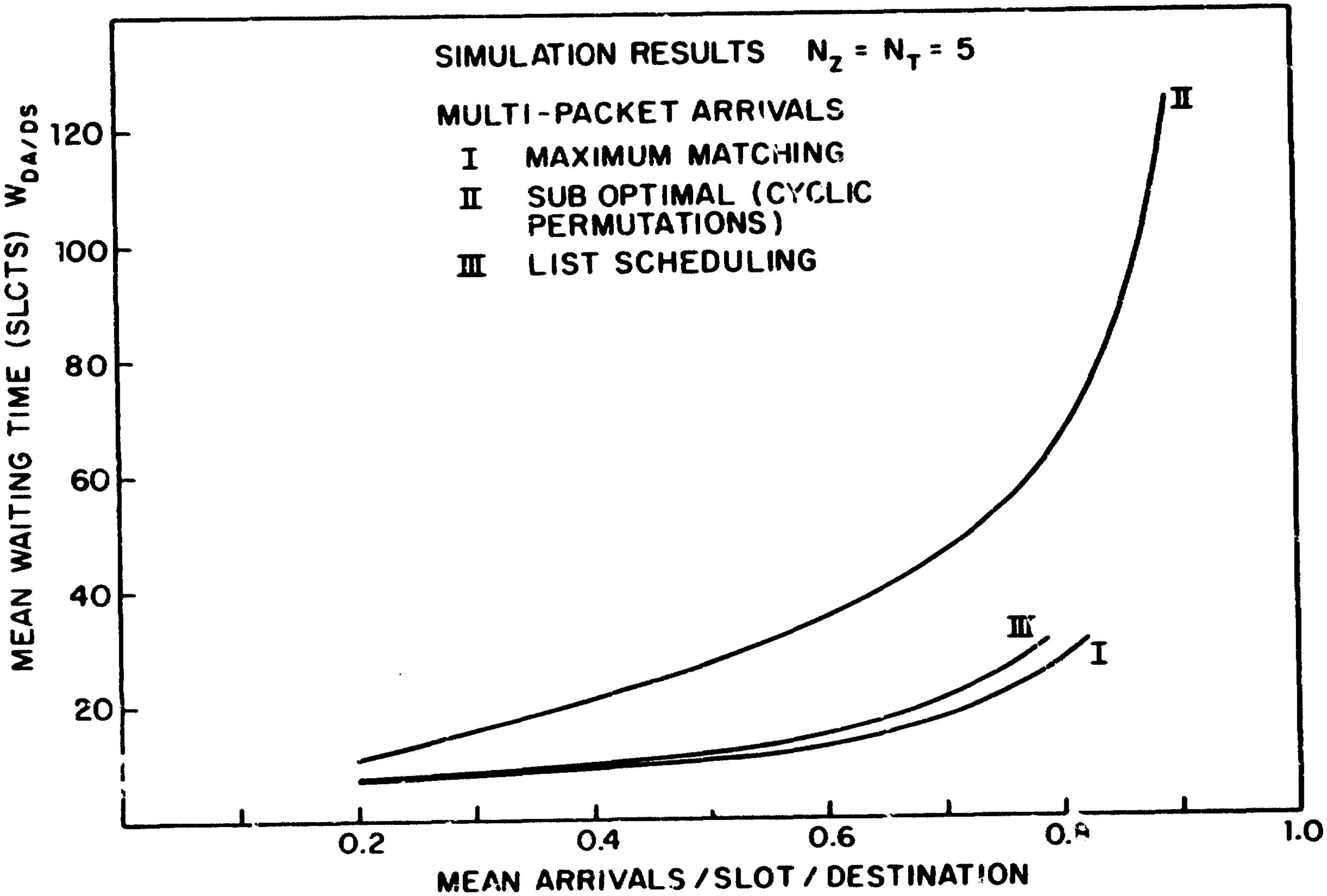


FIG. 4.5 WAITING TIME CURVES (DA/DS), MULTIPACKETS

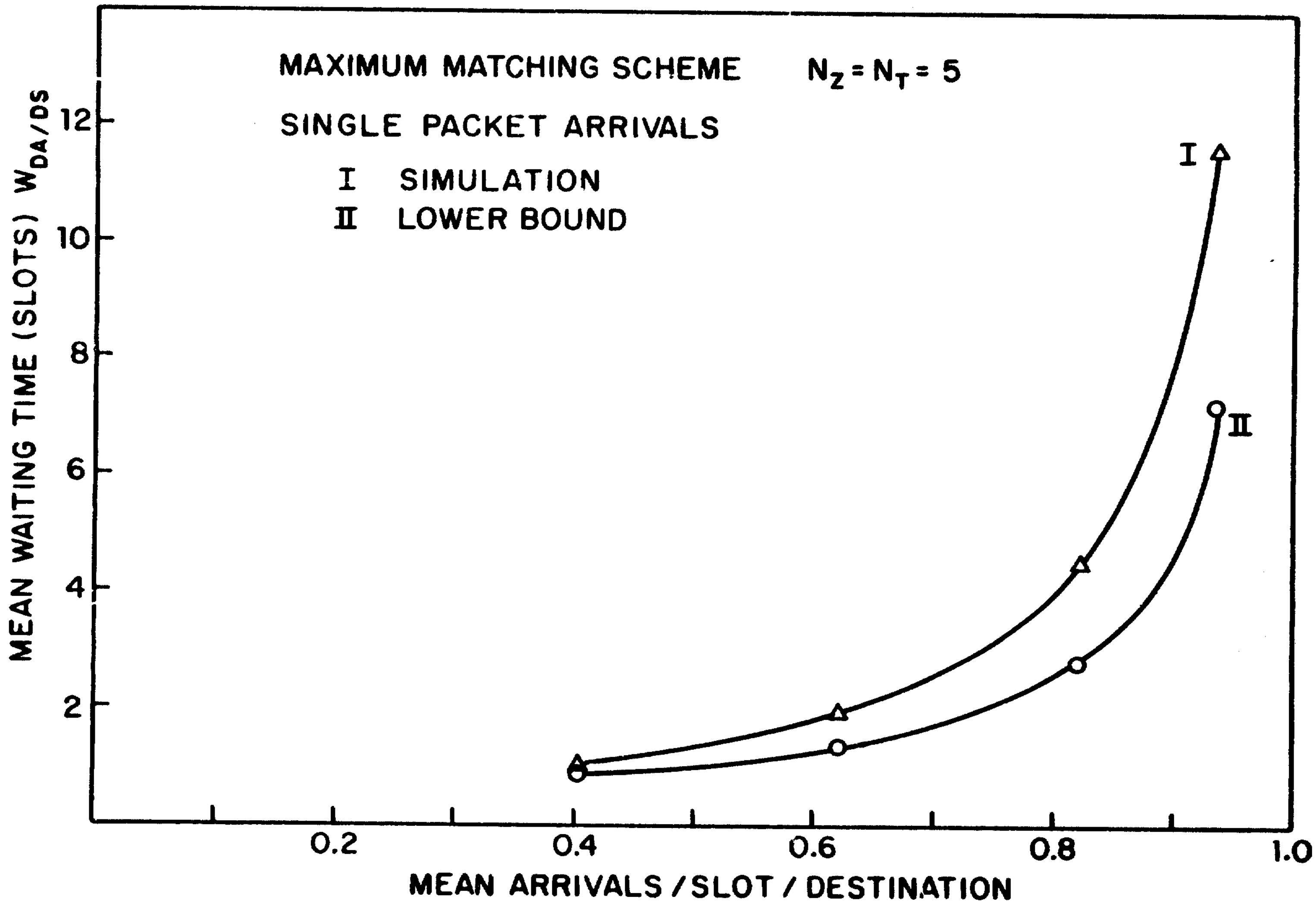


FIG. 4.6 LOWER BOUND ON WAITING TIME (DA/DS), SINGLE PACKETS

A-EC-2059 WL.

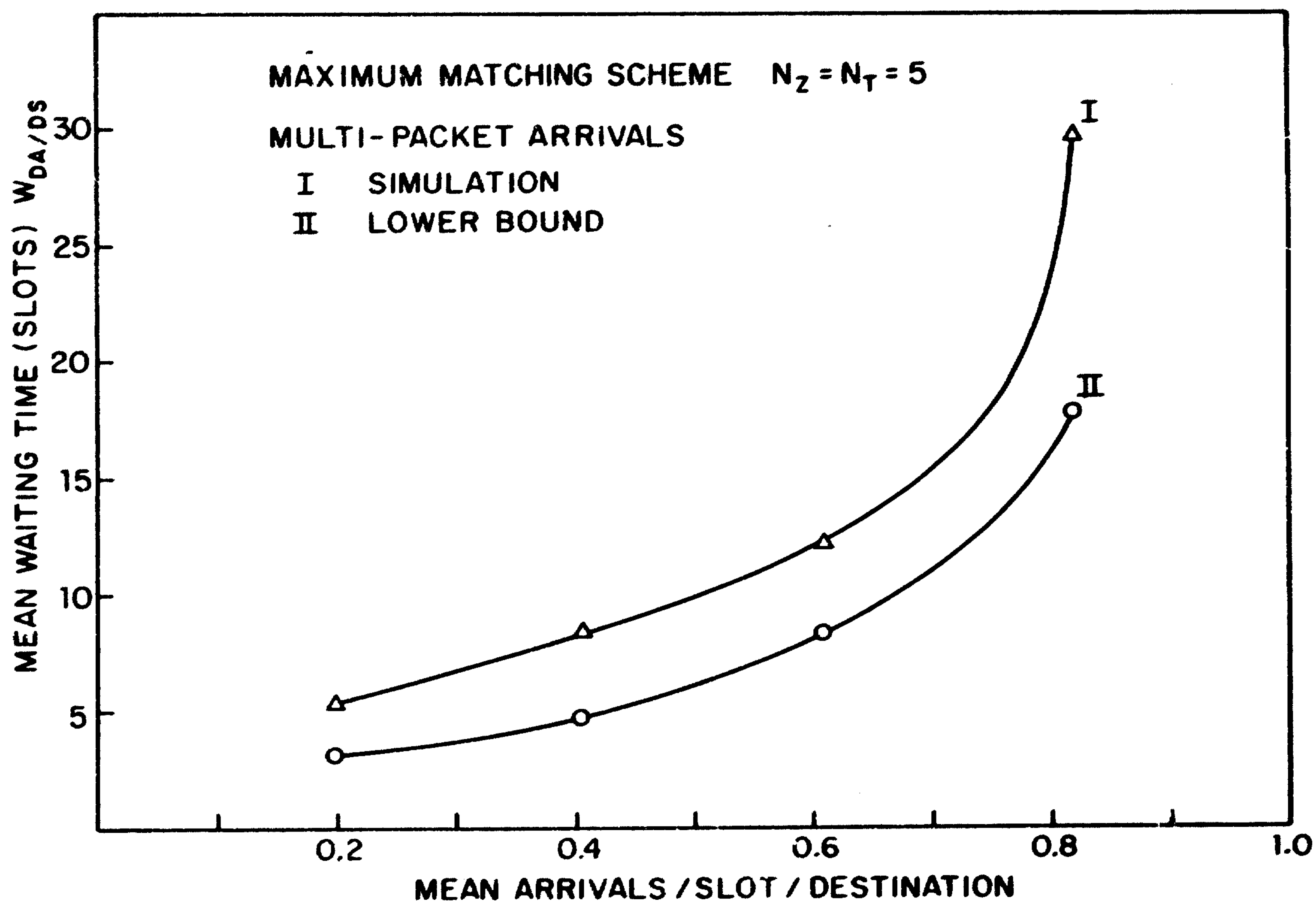


FIG. 4.7 LOWER BOUND ON WAITING TIME (DA/DS), MULTIPACKETS

FIG. 4.8 STATE DIAGRAM FOR BIRTH-DEATH PROCESS

A·EE-2060 W.L.

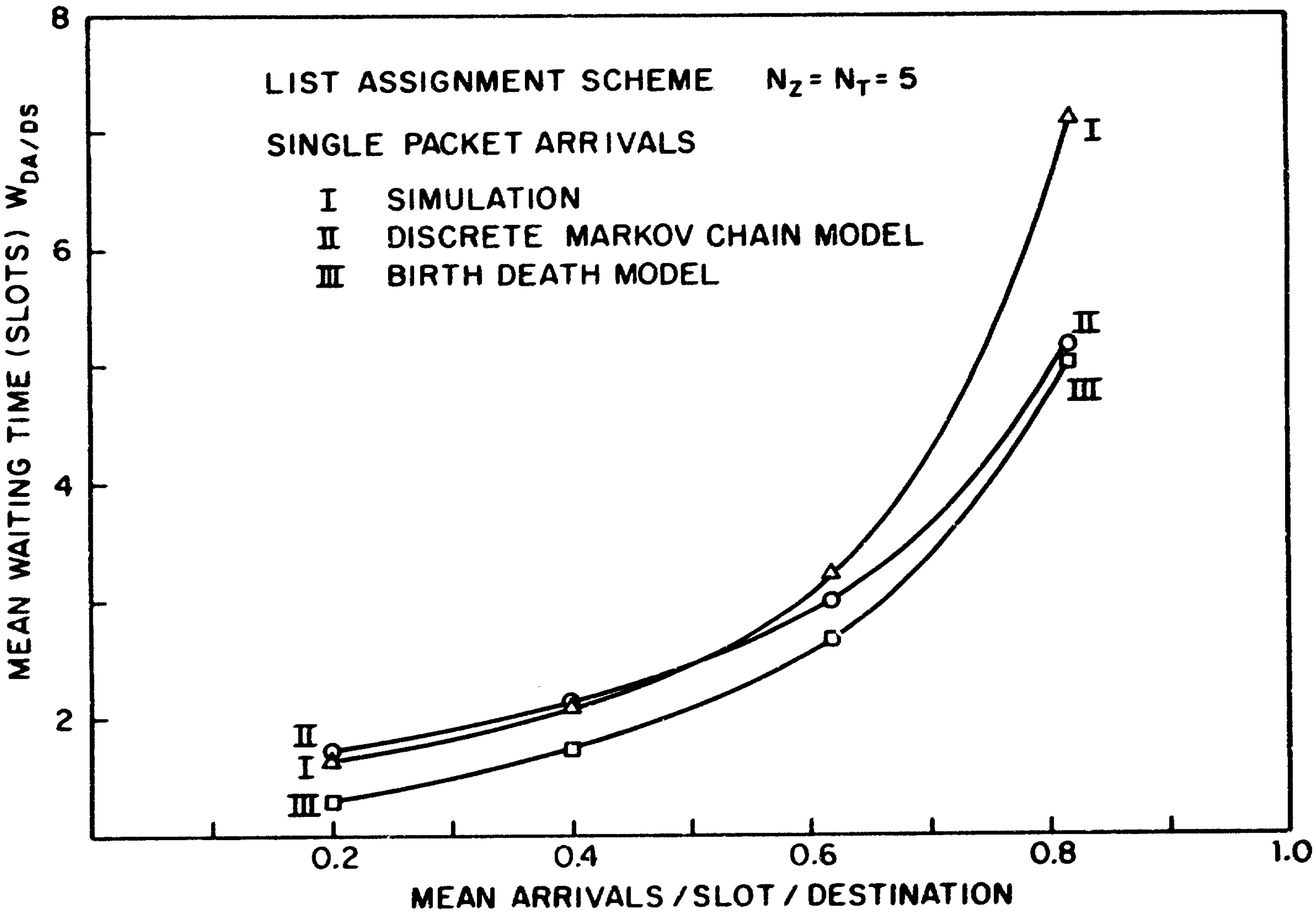


FIG. 4.9 WAITING TIME VIA MARKOV MODELS

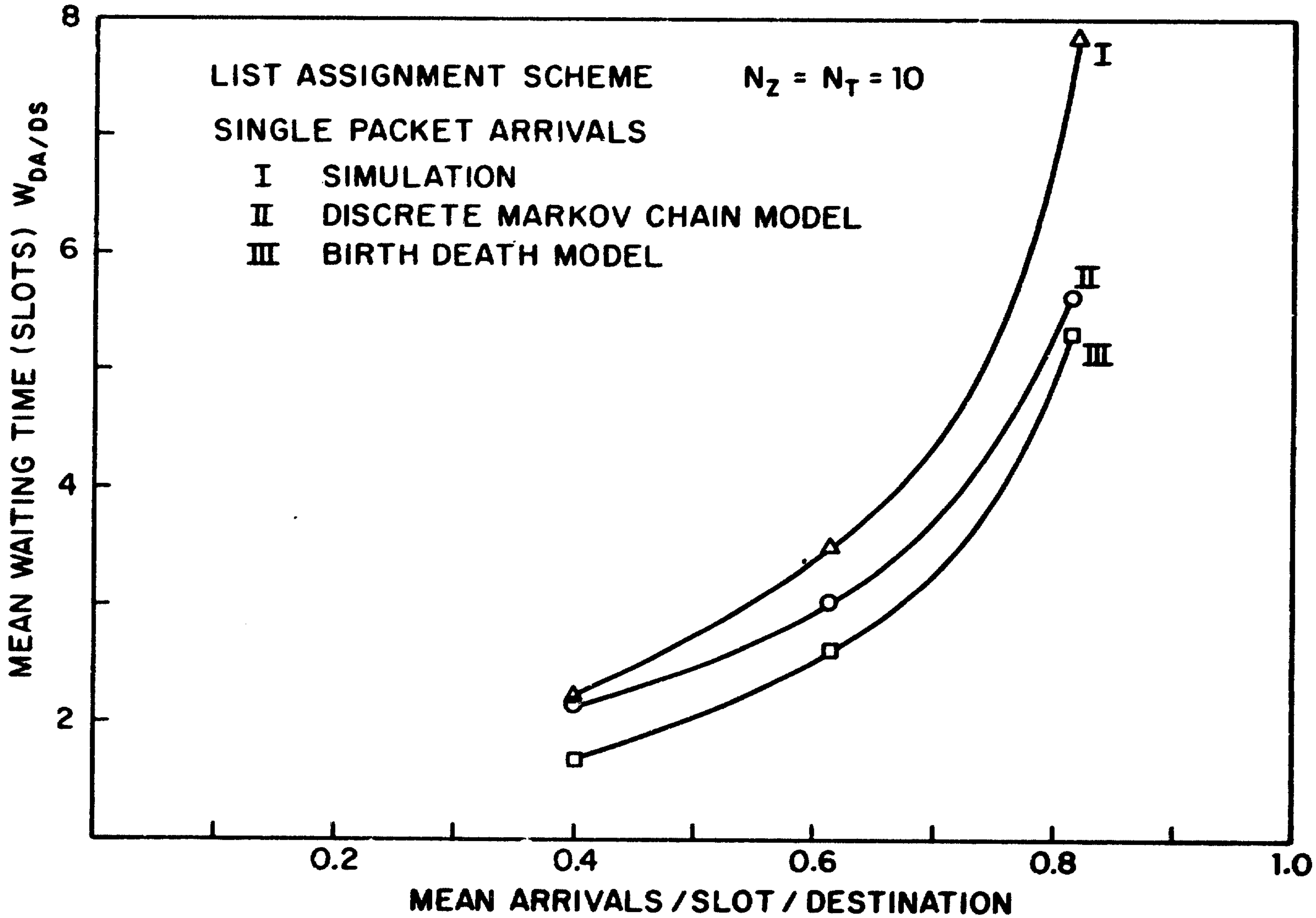


FIG. 4.10 WAITING TIME VIA MARKOV MODELS

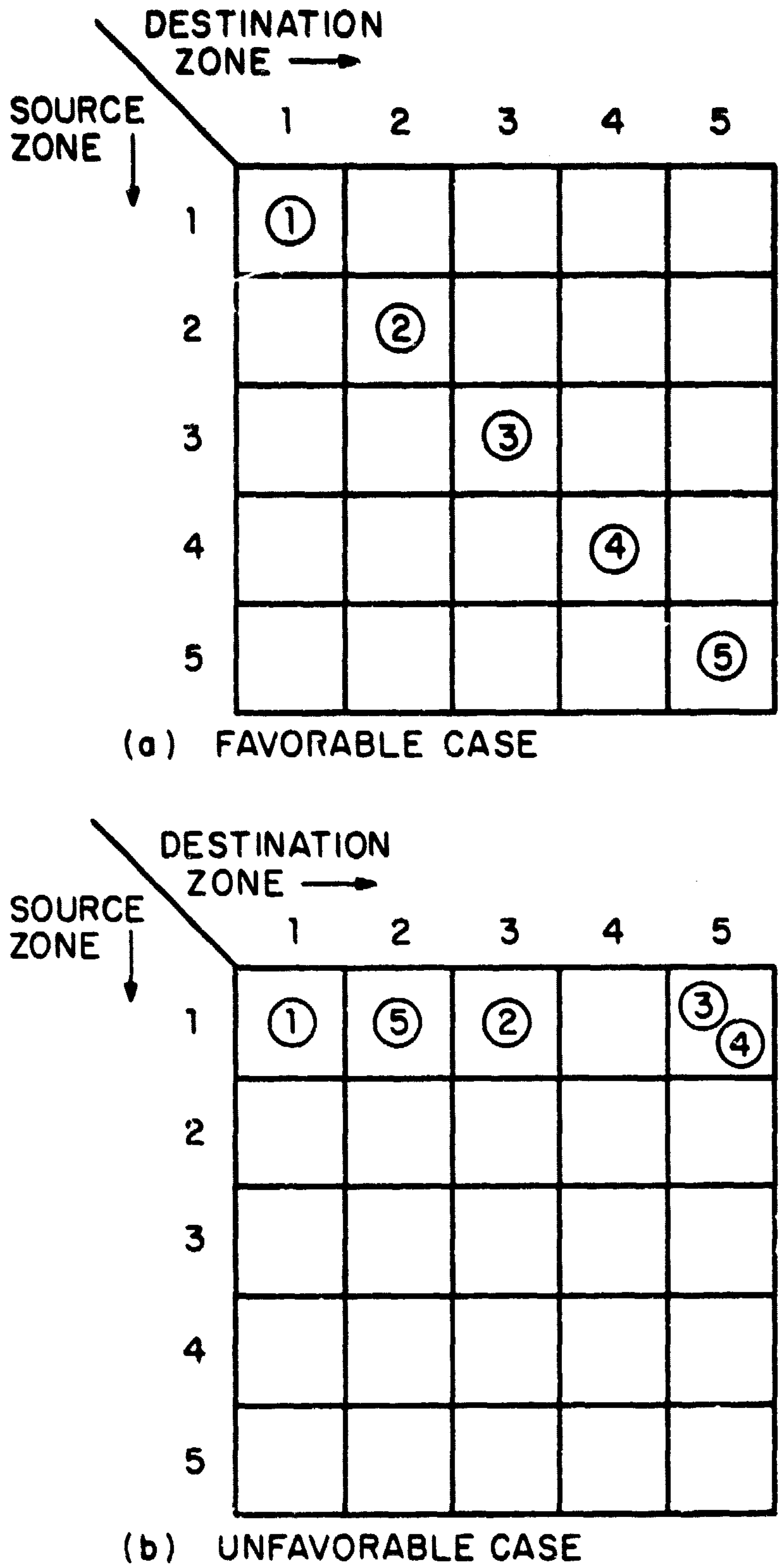


FIG. 4.11 CONTRASTING EXAMPLES OF PENDING REQUESTS

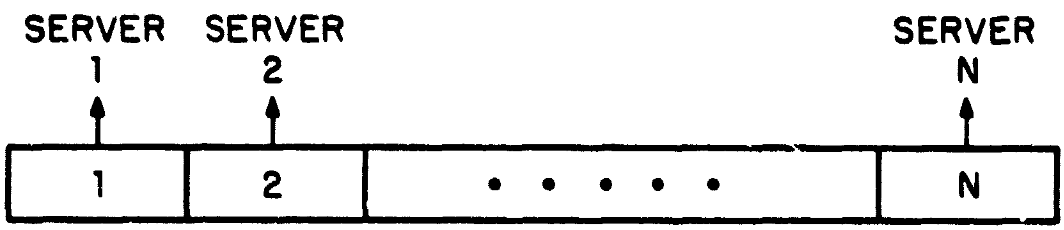


FIG. 4.12 N-QUEUE, N-SERVER SYSTEM

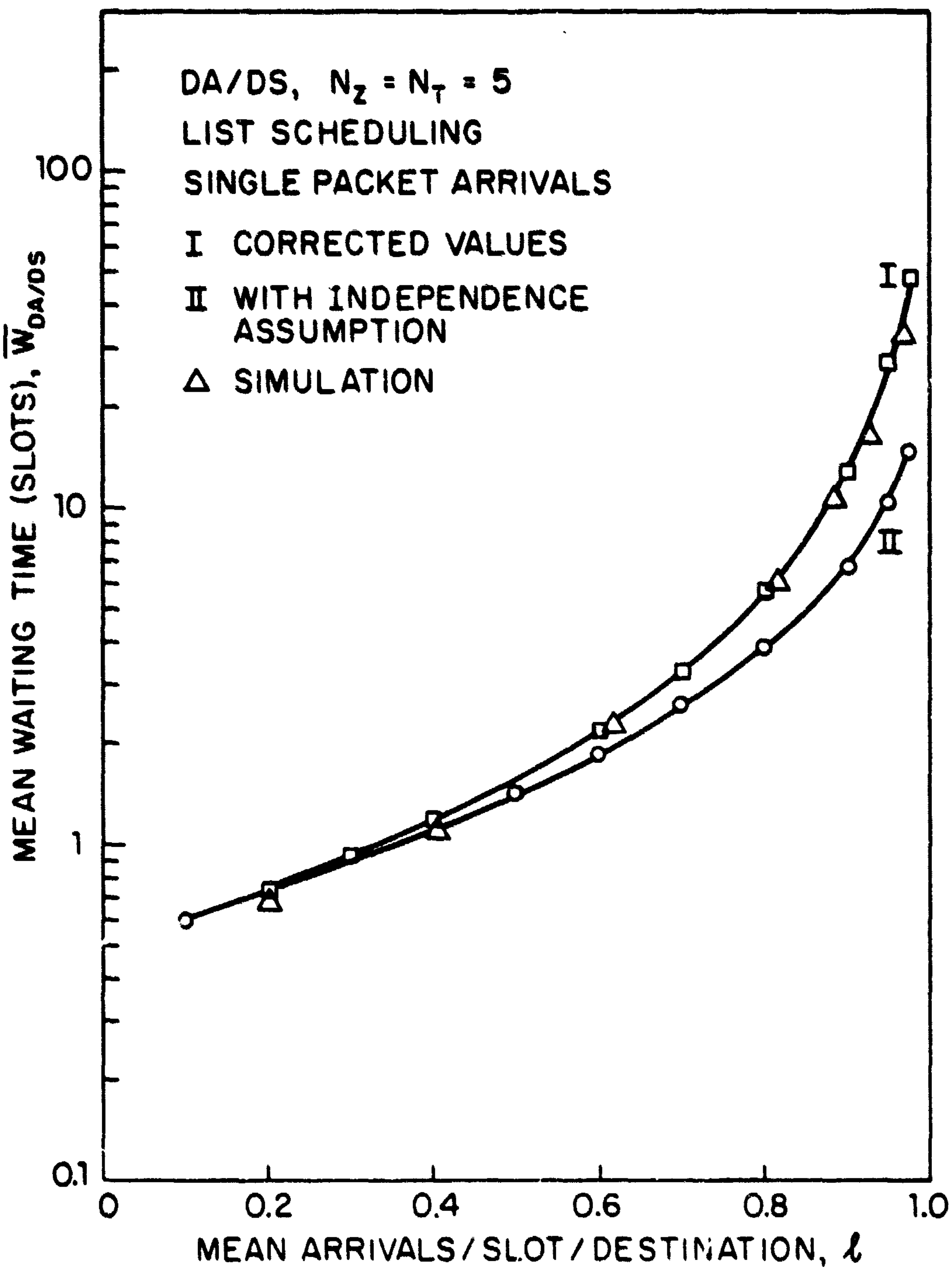


FIG. 4.13 WAITING TIME VIA CORRECTED MARKOV MODELS, SINGLE PACKETS

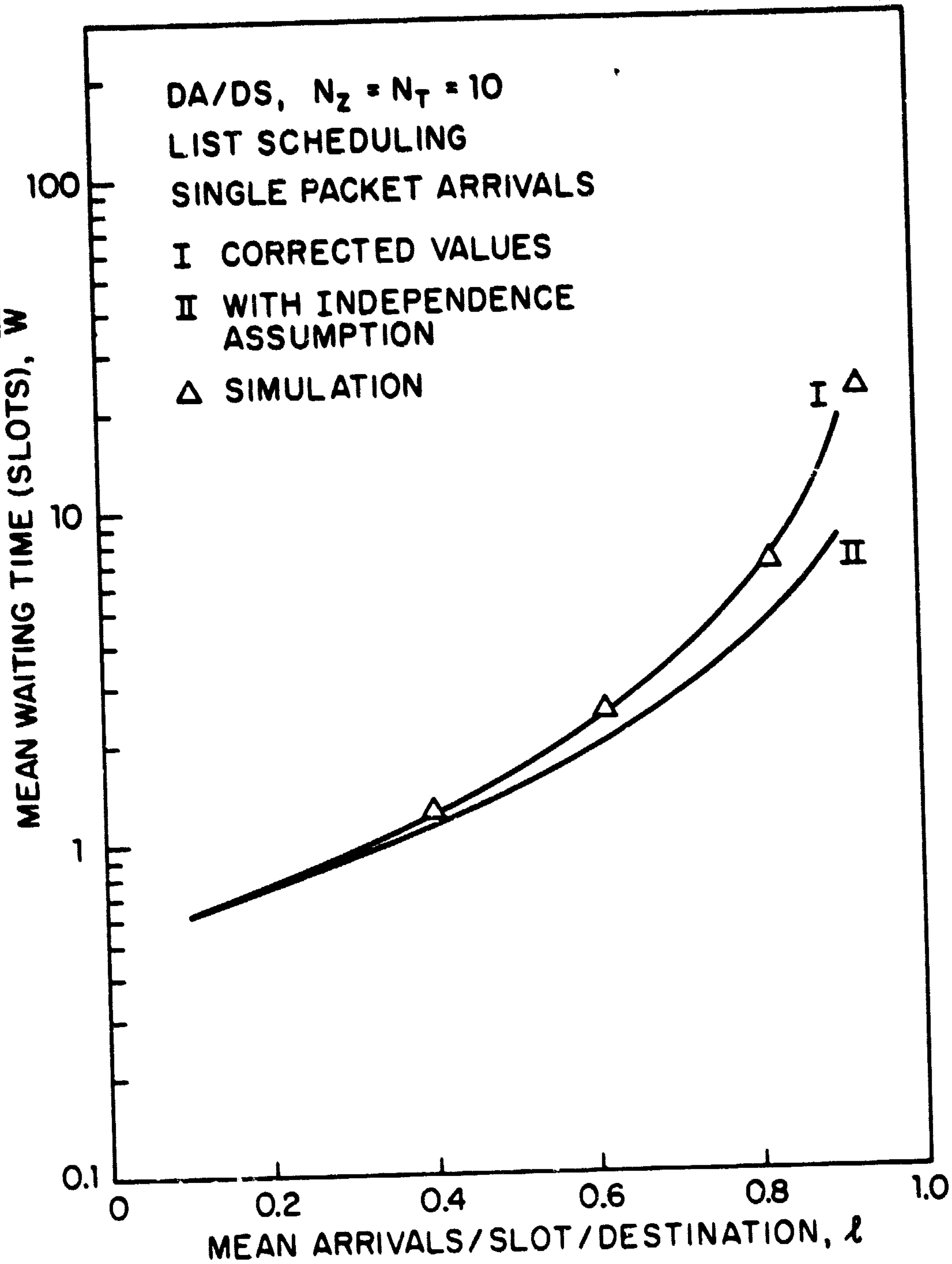


FIG. 4.14 WAITING TIME VIA CORRECTED MARKOV MODELS, SINGLE PACKETS

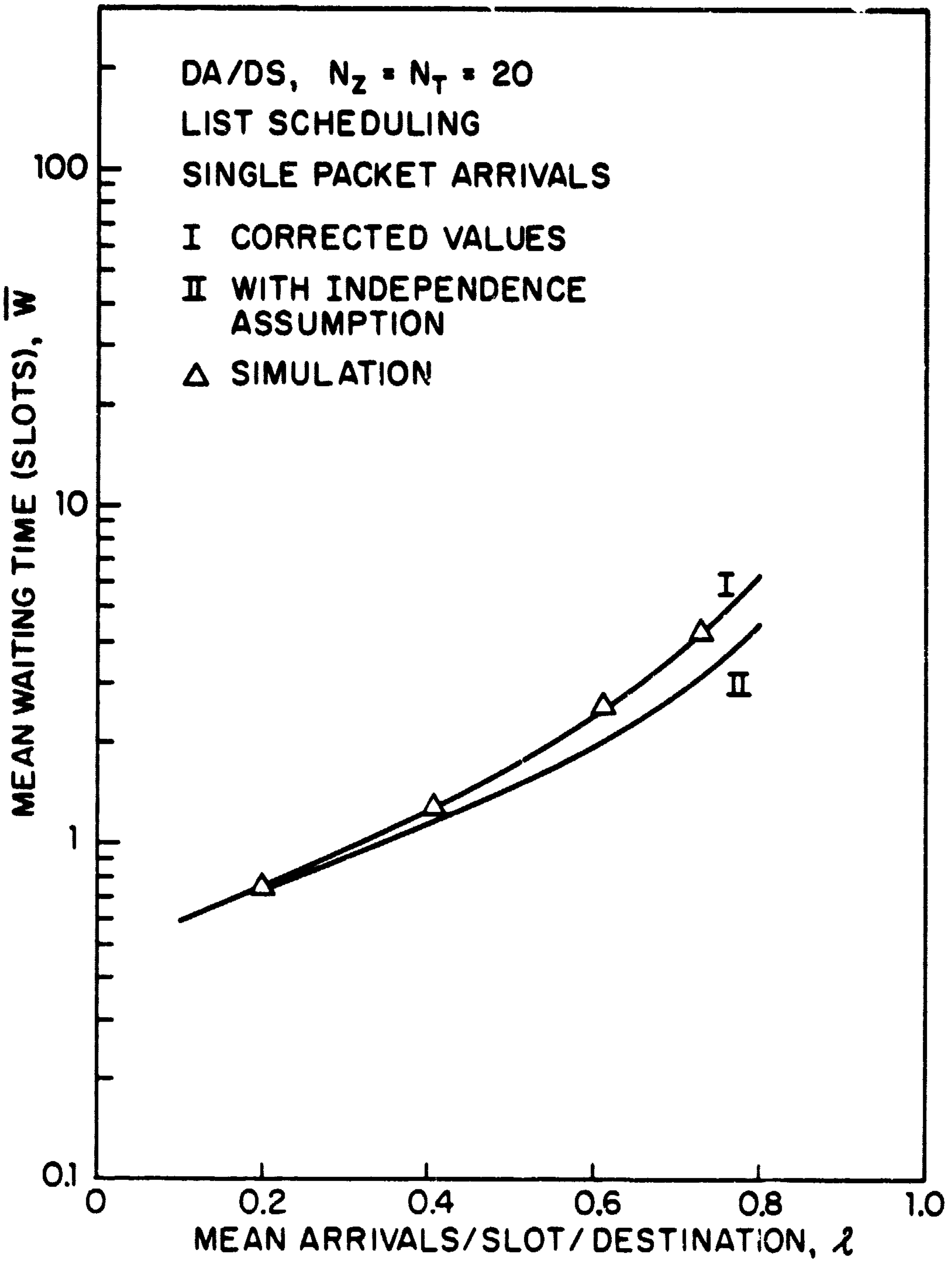


FIG. 4.15 WAITING TIME VIA CORRECTED MARKOV MODELS, SINGLE PACKETS

A-65-2066 WL

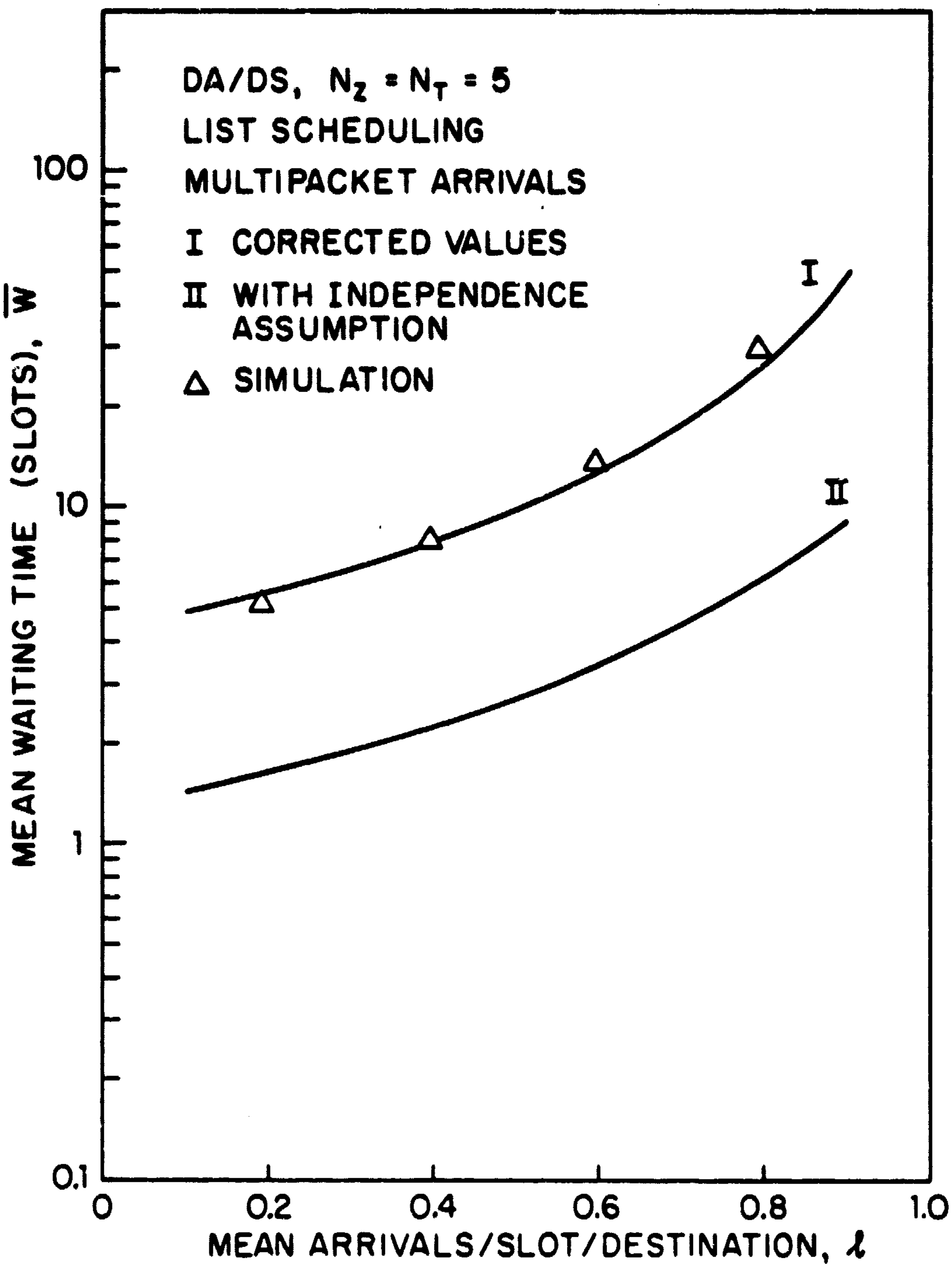


FIG. 4.16 WAITING TIME VIA CORRECTED MARKOV MODELS, MULTIPACKETS

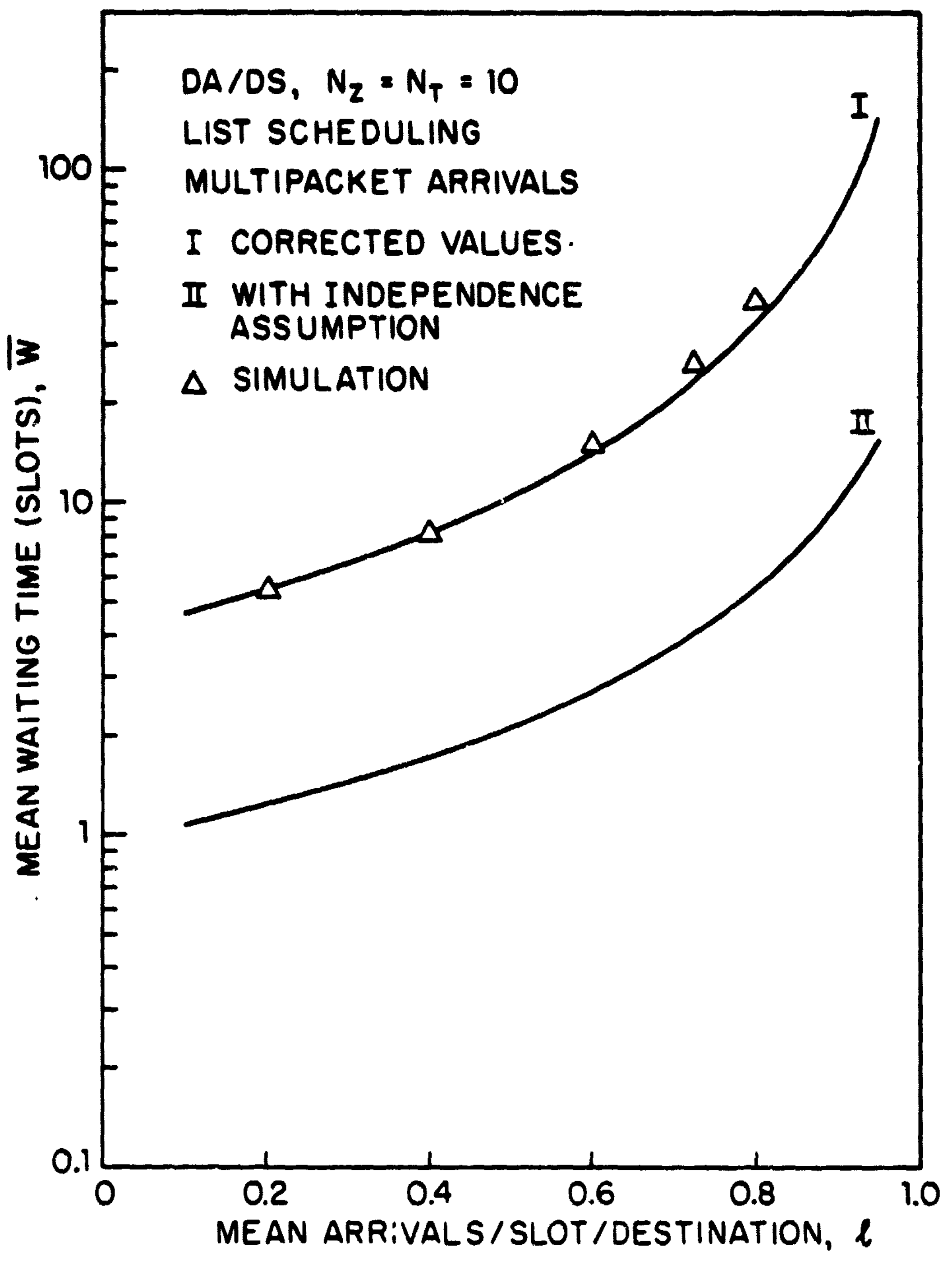


FIG. 4.17 WAITING TIME VIA CORRECTED MARKOV MODELS, MULTIPACKETS

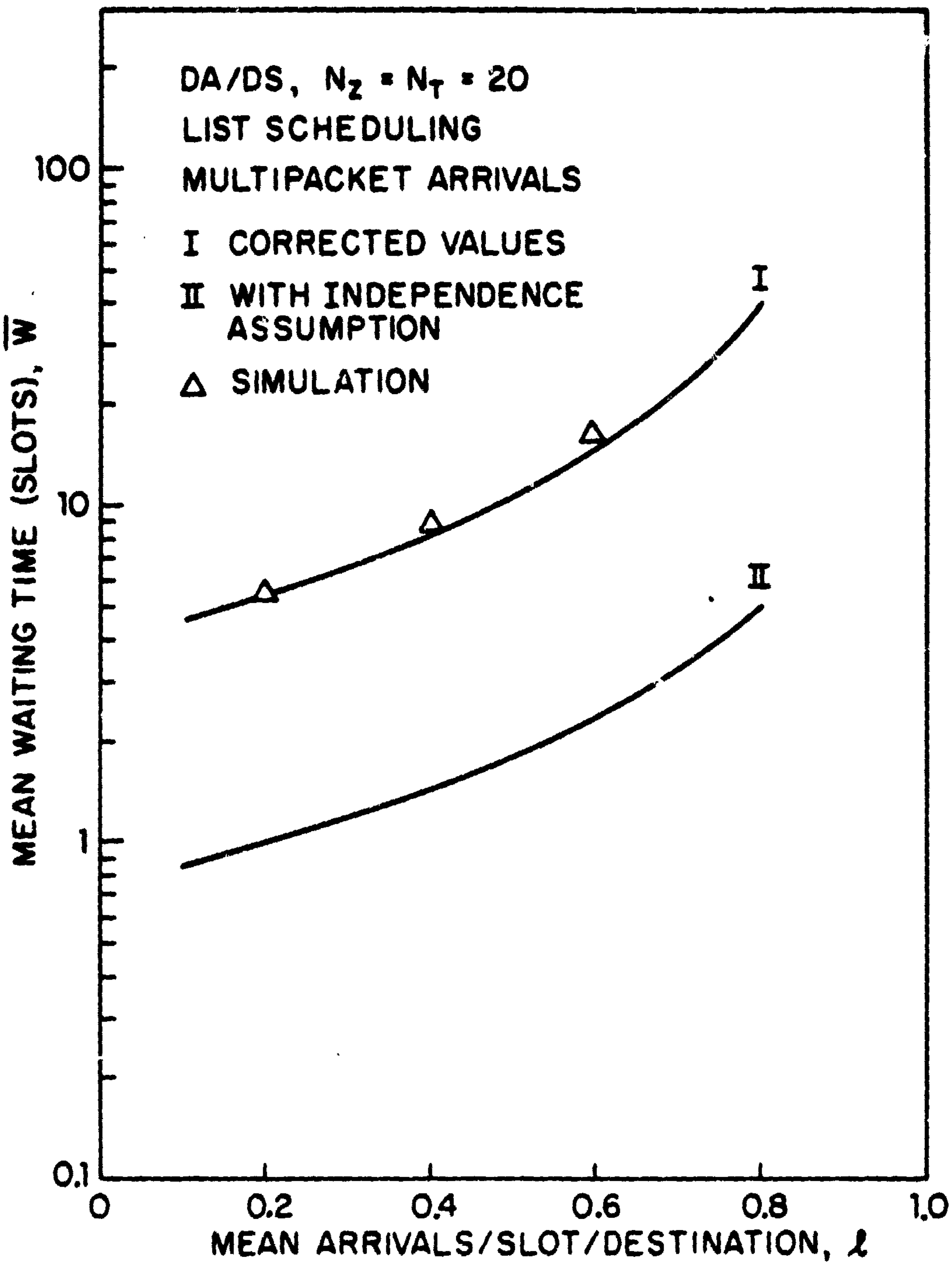


FIG. 4.18 WAITING TIME VIA CORRECTED MARKOV MODELS, MULTIPACKETS

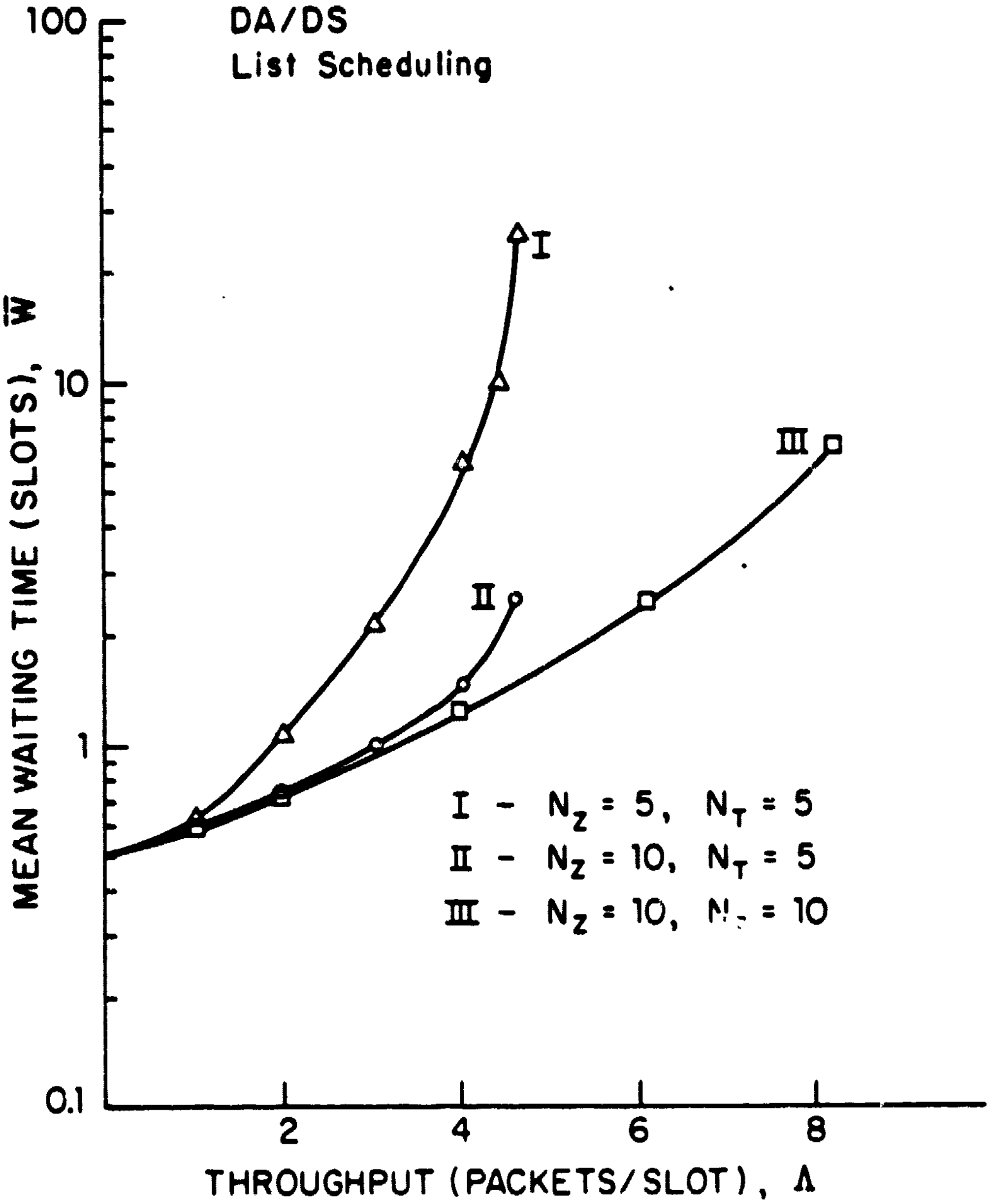


FIG. 4.19 COMPARISONS OF WAITING TIMES FOR DIFFERENT VALUES OF N_T, N_Z

A EE-1917 N.L.

CHAPTER 5

DELAY STUDIES OF SF SYSTEMS

In this chapter, we conclude our delay studies with an analysis of average packet delays in store-and-forward satellite systems. In these systems, transmissions received on the uplink are demodulated and queued in buffers on board the satellite for the appropriate downlink transmissions. Thus, any packet transmitted in this system must pass through two queues - one at the station waiting for access to the uplink and the other on the satellite for the downlink. We consider the behavior of these two queues in the DA/SF systems, presenting analytic results and comparing them with simulations. This is followed by analysis for the FA/SF system. Finally we give numerical examples for the calculation of overflow probabilities of the satellite queues. These calculations are important for determining appropriate buffer sizes onboard the satellite.

5.1 DA/SF SYSTEMS:

Fig. 5.1a shows the queueing model for the DA/SF system for the case $N_z = N_T$. Each zone has one "virtual" queue for all uplink transmissions irrespective of the destination zone. Similarly on the satellite, there is one queue corresponding to each of the downlink zones.

The analysis of the first queue is similar to that of the DA/FS system of Chapter 3. The frame structure for uplink transmission is similar to the DA/FS frame with the difference that now, the frame length is one slot. Thus, we can use Eq.(3.4) for the waiting time $\overline{W}_{DA/SF1}$, for the station uplink queue, obtaining

$$\overline{W}_{DA/SF1} = \frac{\overline{Q}}{\rho} - \frac{1}{2} \text{ slots} \tag{5.1}$$

where $\overline{Q}$ is given by Eq.(3.3).

The frame for the downlink transmission is also one slot long. However, the analysis for the downlink queues is more complicated due to the complex nature of the arrival process to these queues. To facilitate analysis, we assume that packet arrivals to each of the downlink queues are independent Poisson processes. We note that with finite N_z, there are a finite number of input sources to these queues so that the Poisson assumption is not quite true. However, we expect the approximation to be close as the number of zones becomes large. The Poisson assumption also implies that there is no correlation between the number of packets arriving in consecutive slots. This is accurate for the case of single packet messages. However, in the multipacket case this is not true since with the FIFO rule, packets from the same message arrive in consecutive slots.

Using the Poisson assumption, the analysis of the downlink queue is similar to the uplink queues and we have

$$\overline{W}_{DA/SF2} = \frac{\overline{Q}}{\rho} - \frac{1}{2} \text{ slots} \tag{5.2}$$

We note that when calculating $\overline{Q}$ for the downlink case, we assume single packet arrivals even for the case of multipacket arrivals in the uplink queues.

In order to determine the validity of our analytic results, simulations of the store-and-forward system were performed for $N_z = 5$ and 20. Tables 5.1 through 5.4 show waiting times obtained from analysis and simulations for both single and multipacket messages.

Table 5.1 $N_z = N_T = 5$, Single Packets

ρ	$\overline{W}_{DA/SF1}$ (Slots)		$\overline{W}_{DA/SF2}$ (Slots)	
	Analysis	Simulation	Analysis	Simulation
.2	.625	.615	.625	.61
.4	.833	.84	.833	.78
.6	1.25	1.3	1.25	1.21
.8	2.5	2.45	2.5	2.3

Table 5.2 $N_z = N_T = 5$, Multipackets

ρ	$\overline{W}_{DA/SF1}$ (Slots)		$\overline{W}_{DA/SF2}$ (Slots)	
	Analysis	Simulation	Analysis	Simulation
.2	4.51	4.29	.625	1.24
.4	6.019	6.0	.833	2.81
.6	9.028	8.58	1.25	5.1
.8	18.05	16.8	2.5	16.0

Table 5.3 $N_z = N_T = 20$, Single packets

ρ	$\overline{W}_{DA/SF1}$ (Slots)		$\overline{W}_{DA/SF2}$ (Slots)	
	Analysis	Simulation	Analysis	Simulation
.2	.625	.615	.625	.622
.4	.833	.838	.833	.828
.6	1.25	1.29	1.25	1.27
.8	2.5	2.45	2.5	2.48

Table 5.4 $N_z = N_T = 20$, Multipackets

ρ	$\overline{W}_{DA/SF1}$ (Slots)		$\overline{W}_{DA/SF2}$ (Slots)	
	Analysis	Simulation	Analysis	Simulation
.2	4.51	4.4	.625	1.37
.4	6.019	5.96	.833	2.87
.6	9.028	8.58	1.25	6.14
.8	18.05	17.2	2.5	13.62

From these tables, it is clear that the analytic results agree quite well with the simulations for the single packet case. As expected, the agreement is closer for the case $N_z = 20$ as compared to the case $N_z = 5$. The results for the multipacket case however, do not agree with simulations. The Poisson assumption appears to be too optimistic. We note from the tables that if we assumed the same arrival process for the uplink, the waiting times obtained from analysis would be higher than those for simulations. The results of analysis will be used henceforth for the single packet case only. For the multipacket case, we shall rely on the results of simulation.

Finally, considering the case where $N_z > N_T$, the behavior of the uplink queues is identical to the previous case and Eq.(5.1) still holds. On the downlink, we now have N_T transponders serving N_z queues and so, the packets see a frame structure on the downlink in which the frame length is $\sim N_z/N_T$ slots long. Thus Eq.(5.2) is still true with the units changed to frames.

5.2 FA/SF SYSTEMS

The queueing model for the FA/SF system for $N_z = N_T$ is shown in Fig. 5.1b. On the uplink, we now have a frame structure in which each station in a zone is allocated one slot per frame (for balanced traffic). Thus the frame is N_s slots long and the waiting time on the uplink queue is given as

$$\overline{W}_{FA/SF1} = \frac{\overline{Q}}{\rho} - \frac{1}{2} \quad \text{frames} \tag{5.3}$$

For this case there are still N_z input sources feeding each downlink queue, and the Poisson assumption for the single packet case is valid. We note that in the multipacket case now, the Poisson assumption is also quite good because there is no correlation between packet arrivals in consecutive slots. In fact, there is no correlation between packet arrivals in any N_s consecutive slots. Thus, in FA/SF systems we reply on the Poisson assumption for the downlink queues for both single and multipacket messages. The frame structure on the downlink is the same as in the DA/SF case and we have

$$\overline{W}_{FA/SF2} = \frac{\overline{Q}}{\rho} - \frac{1}{2} \text{ slots} \tag{5.4}$$

with $\overline{Q}$ given by Eq. (3.2).

These results can be extended to the case $N_z > N_T$ in a manner similar to that given for the DA/SF system.

5.3 BUFFER REQUIREMENTS

We now present analysis to obtain overflow probabilities for a finite onboard buffer. These results are valid only for the single packet case and for $N_z = N_T$. Instead of using the Poisson assumption for input to the downlink queues, we take the approach of Rudin [RUD 71] in what follows.

The contents of the satellite queue are modelled using the following definitions

$M(k)$ = Number of packets in the queue just prior to the beginning of the k^{th} slot.

$N(k)$ = Number of new packets arriving in the k^{th} slot

$P_m(k)$ = Prob $[M(k) = m]$

a_n = Prob $[N = n]$

The number of input sources is N_z and so, we have $0 \leq n \leq N_z$. For the probabilities a_n, we assume a binomial distribution

$$a_n = \binom{N_z}{n} (\rho/N_z)^n \, (1-\rho/N_z)^{N_z - n} \tag{5.5}$$

where ρ/N_z is the probability that a packet will arrive from a particular uplink in one slot and will join a particular down-link queue.

The evolution of the system is defined by

$$P_m(k+1) = \sum_{n=0}^{N_z} P_{m+1-n}(k) \, a_n \tag{5.6}$$

For a finite buffer of size Q_M, the overflow probabilities are calculated using an approximation. The system is allowed to take fictitious

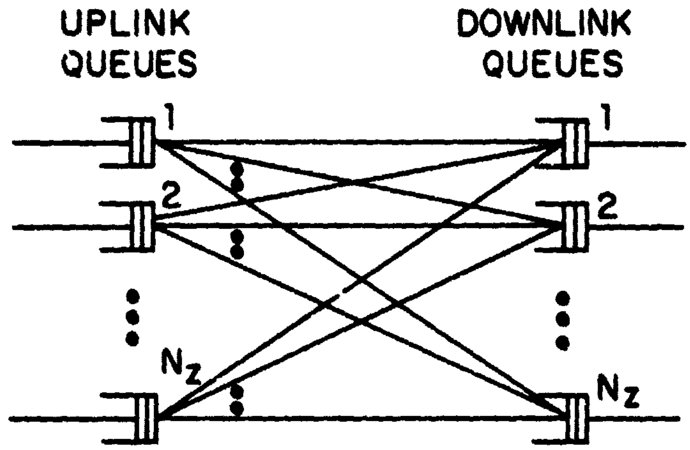
states states $m = -1$, and $m = Q_M + 1$ to $Q_M + N_z - 1$. Thus, the allowable values for m are $-1 \le m \le Q_M + N_z - 1$. Values of P_m, the ergodic probabilities, are computed for all these states and the overflow probability is obtained as

$$P_{ov} = \sum_{i=1}^{N_z-1} P_{Q_M+i} \tag{5.7}$$

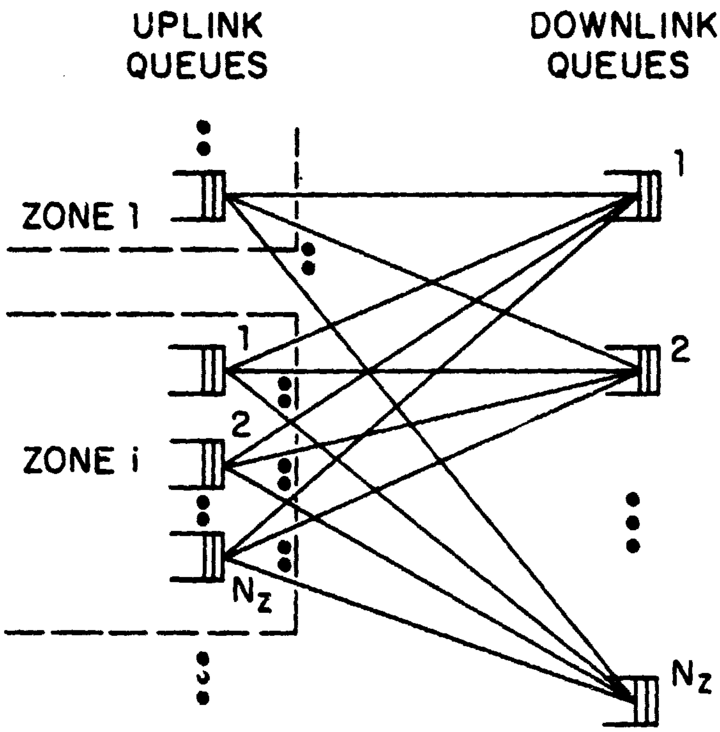
Using this method, we obtain the following numerical results. For $\rho = .9$, $N_z = 20$ and an overflow probability of 10^{-3}, a buffer of 20 packets/zone is required. Thus for packets of length L = 2000 this implies 800 kbits of storage. For $\rho = .6$ and P_{ov} of 10^{-3}, the buffer requirement is reduced to 6 packets/zone for the 20 zone system.

In this analysis, we have assumed that each downlink has a dedicated buffer. Buffer requirements can be reduced somewhat by sharing the buffers among all downlink queues [IRL 78] . Also, it should be noted that in the multipacket case, buffer requirements would be higher.

$N_Z = N_T$



(a) DA/SF SYSTEM



(b) FA/SF SYSTEM

FIG. 5.1 QUEUING MODEL FOR THE SF SYSTEMS

CHAPTER 6

PERFORMANCE COMPARISON

In this Chapter, we compare the six access protocols (FA/FS, DA/FS, RA/FS, DA/DS, FA/SF and DA/SF) using specific values of system parameters. Average packet delays are calculated for each of the schemes by using the appropriate waiting time expressions of Chapters 3,4 and 5 with the time delay expressions of Chapter 2. In the DA/FS and DA/SF schemes, we assume that demand station access is realized by using a terrestrial control channel, thereby avoiding an additional propagation delay that would be incurred if a satellite order wire were used. The list scheduling algorithm (requiring a satellite order wire) is assumed for demand switching.

6.1 PERFORMANCE CURVES

We consider a system with capacity C of 200 kbps per transponder. Packets are assumed to be of length 2000 bits giving slot length Δ=10 ms. We assume that $N_Z = N_T = 20$ and that there are 50 stations per zone. The frame size F = 10 sec for FA/FS, 200 ms for DA/FS and RA/FS and 500 ms for FA/SF.

The average packet delay $\bar{T}$ is plotted in Fig. 6.1 and 6.2 as a function of ρ the traffic intensity (packet arrival rate/system capacity in packets per second). In both cases of message arrival statistics (single packets in Fig. 6.1 and multipackets in Fig. 6.2), the DA/SF scheme is superior for all values of ρ. However, the SF systems possess the serious disadvantage of requiring on board demodulation, remodulation and buffering capability as well as a terrestrial control network. The FA/SF scheme performs relatively poorly (because of the 500 ms frame size), while still requiring the aforementioned onboard processing. The RA/FS scheme (shown only for single

packet case) as expected, performs well only for very low traffic intensities (throughputs) saturating at $\rho \sim .37$. Because of these deficiencies of the DA/SF, FA/SF schemes, we have concentrated our attention on the remaining three schemes.

For the case of single packet arrivals, it can be seen that the DA/FS scheme performs better for lower values of ρ but for values of ρ greater than .7, the DA/DS scheme is superior. For the multipacket case, however, the DA/DS scheme is clearly superior for all values of ρ, suggesting that DA/DS can best be utilized for traffic environments which involve long messages. In both cases, the performance of the FA/FS scheme is poor for all values of ρ, its advantage being its simplicity. (It should be recalled that DA/FS, as opposed to FA/FS requires extra control, assumed here to be implemented through a low capacity terrestrial network. This of course involves extra cost and complexity.)

6.2 EFFECT OF SYSTEM PARAMETERS ON PERFORMANCE (FA/FS, DA/FS, DA/DS)

When comparing these schemes, the choice of system parameters is very important in determining the superiority of one over the other. In the last section, the importance of message length statistics was demonstrated. Two other system parameters are very important - the transponder capacity C and the number of zones N_z.

Figure 6.3 shows the effect of N_z where $\overline{T}$ vs N_z curves are plotted for the three access techniques now being considered, with $\rho = .8$, $N_T = N_z$ and single packet messages. The DA/DS scheme is superior when the system has a large number of zones ($N_z > 12$ for this example) For smaller values of N_z the DA/FS scheme has better performance. Again, the FA/FS scheme is poor for all values of N_z.

The effect of system capacity C on the performance curves is illustrated in Fig. 6.4. Here, values of $\overline{T}$ are plotted as a function of C with $\rho = .8$ and $N_z = N_T = 20$. For the range considered, the DA/DS scheme is superior but simple calculations show that for large values of C (> 2.4 Mbps in this example), the DA/FS scheme is best. In addition, comparison of Figs. 6.3 and 6.4 provides some insight into the influence of the number of stuations per zone and the message length (in packets) on packet delay. The frame length for FA/FS systems increases as the number of stations (N_s) increases whereas the frame length for DA/FS system is not dependent on N_s. This results in large delays for FA/FS system with large N_s as explained in the following paragraph.

The relative performance of the access protocols as expressed in Figs. 6.1-6.4 is easily explained in terms of queueing delay vs propagation delay. The DA/DS scheme consolidates the queueing of all traffic into a single request list, thus greatly reducing queueing delays. As a result, the time delay for this system is approximately 2P for all values of system parameters. (Recall that DA/DS has an extra propagation delay due to the request orderwire). In the FA/FS and DA/FS systems, queueing delay is proportional to frame length, F, with F itself proportional to the number of individual queues maintained in the system. When F becomes comparable to the extra propagation delay incurred in DA/DS, the framed systems performance begins to become inferior to DA/DS. Furthermore, DA/FS, with a frame length shorter than FA/FS, is always superior to FA/FS. Finally, for the DA/SF system, there are two queues but the frame length is one slot (for $N_z = N_T$) and so the time delay is approximately P for all system parameters. Thus, the DA/SF always has superior performance in terms of packet delay.

A summary of equations and simulation block diagrams applicable to the various access and switching schemes is given in Appendix B.

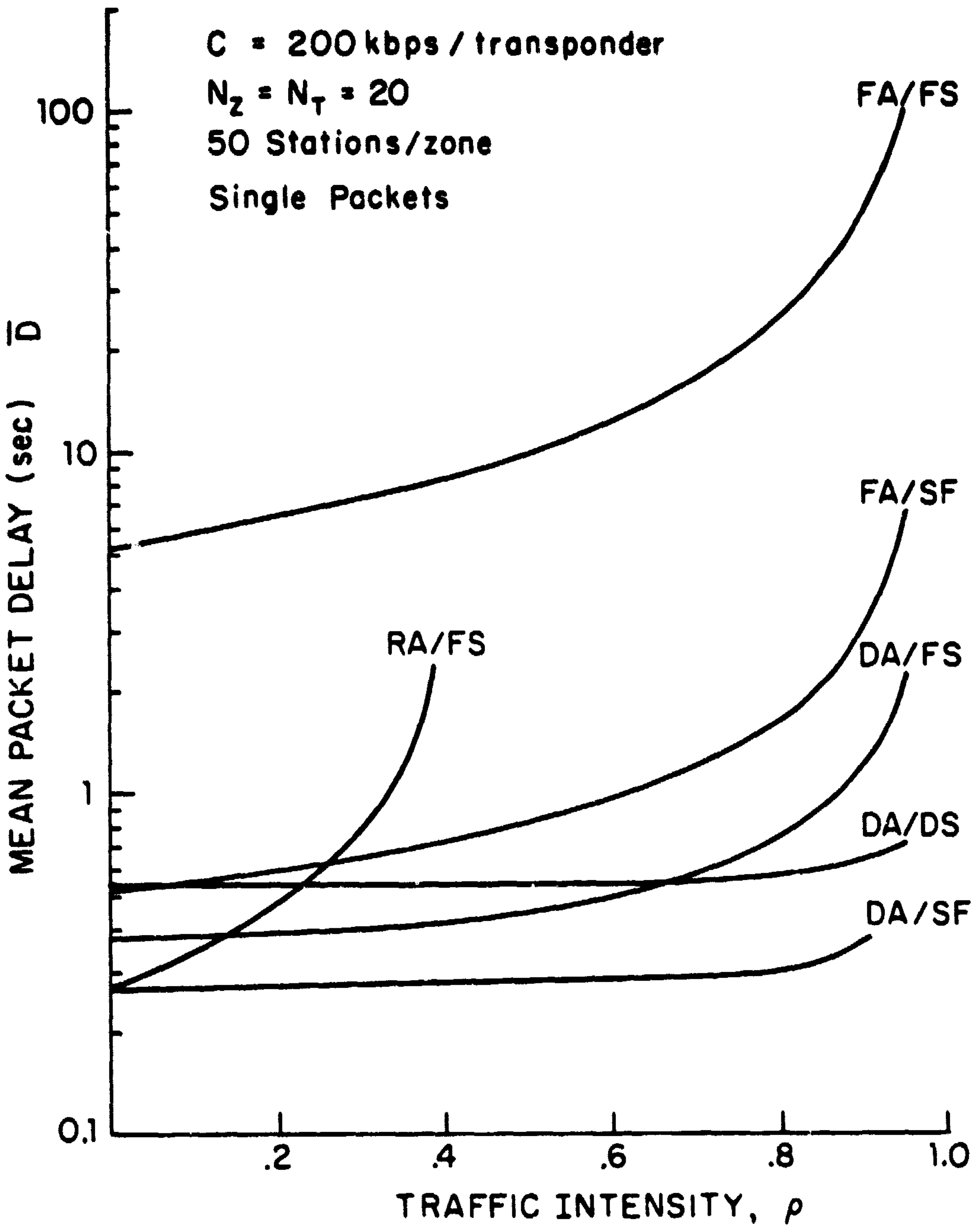


FIG. 6.1 DELAY-THROUGHPUT COMPARISONS, SINGLE PACKETS

A-EE-1915 W.L.

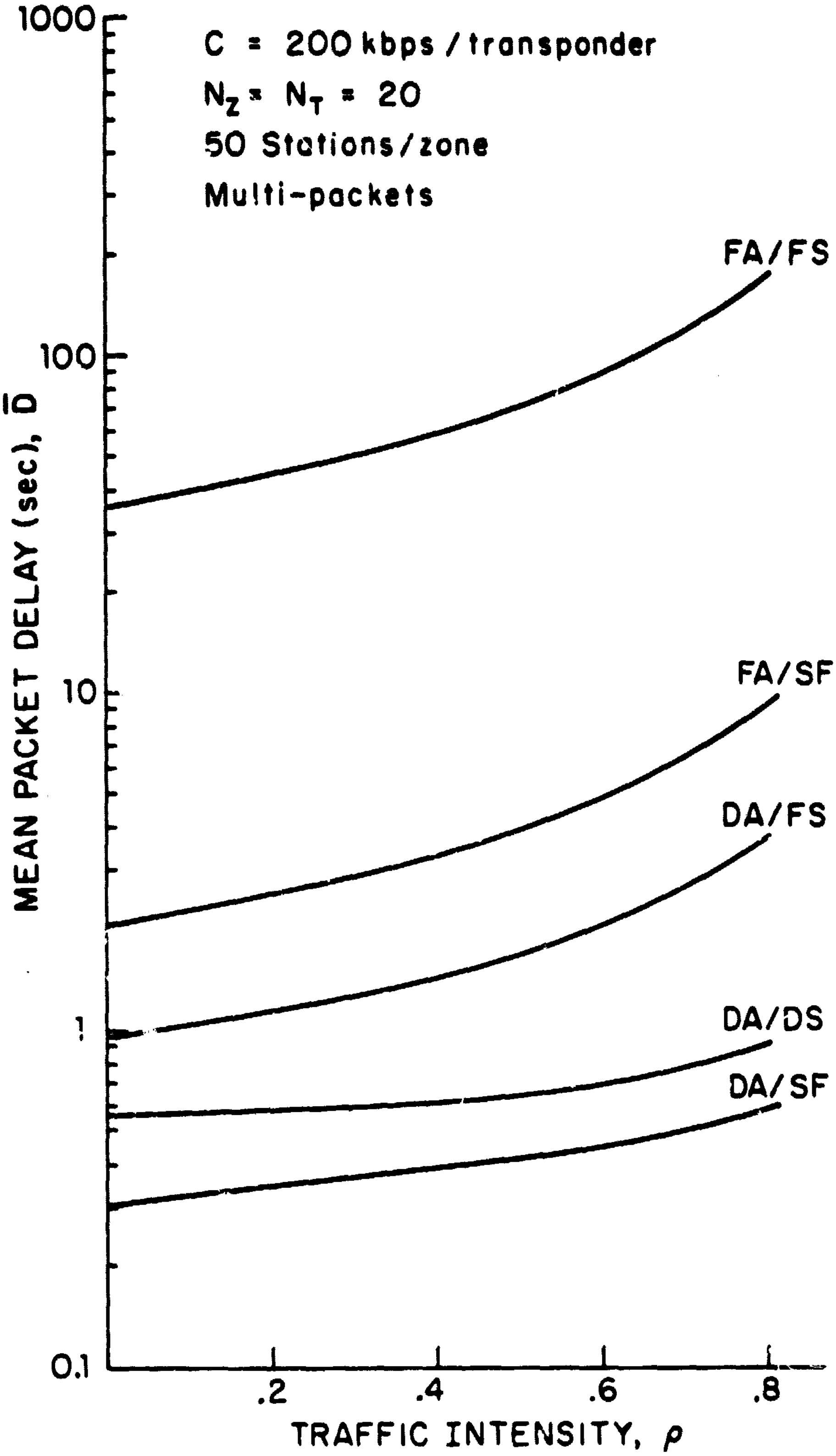


FIG. 6.2 DELAY-THROUGHPUT COMPARISONS, MULTIPACKETS

A-EC-1914 w.c.

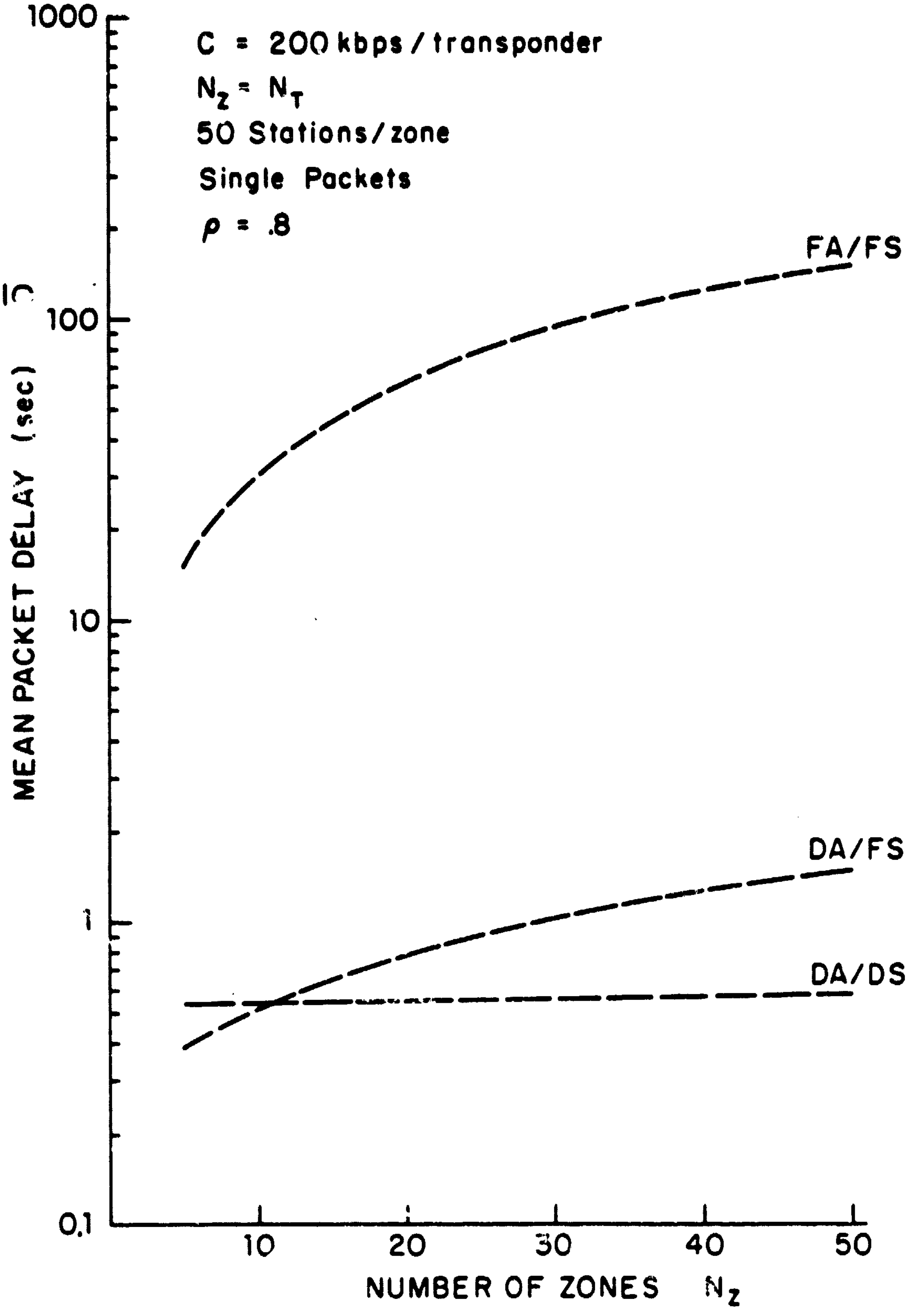


FIG. 6.3 EFFECT OF N_Z ON PACKET DELAY

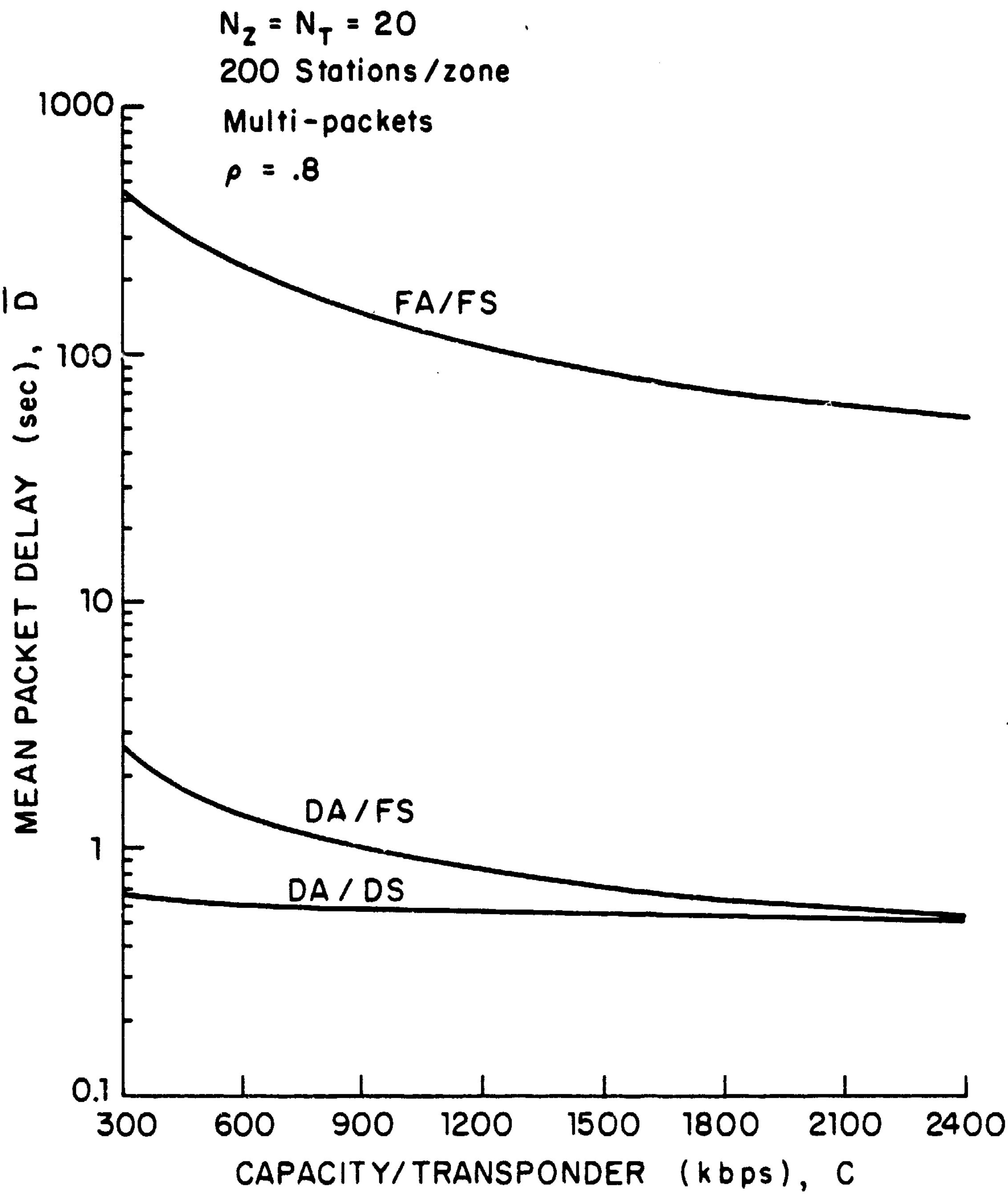


FIG. 6.4 EFFECT OF SYSTEM CAPACITY ON PACKET DELAY

.' EE-191; W.L.

CHAPTER 7

CONCLUSIONS AND SUGGESTIONS FOR FUTURE STUDY

7.1 SUMMARY OF RESULTS AND CONCLUSIONS

The goal of this first phase of our project was to develop and analyze the performance of multiple access techniques for satellite switched multiple beam systems operating in a packet switched mode. The multiple access problem was viewed at two levels - the station access problem and the switch assignment problem. Station access was considered on a fixed, demand and random basis. For demand station access, the use of a low capacity terrestrial control link to resolve station access conflicts was suggested. Use of such a link may, in some cases, be practical since, in the multiple beam configuration, all contending stations (being in the same zone) are located in a relatively narrow geographic area.

For the switch assignment problem, fixed, demand and store-and-forward switching was considered. We proposed a number of algorithms for scheduling of the satellite switch on a demand basis. The maximum matching algorithm was shown to be the optimum but required a heavy computational burden. With the help of simulations, the list scheduling algorithm was shown to be the most promising.

Six access protocols (combining the station access and switch assignment protocols) were selected for study, and delay-throughput analysis was performed for each. Existing results from the literature were used (with appropriate modifications) for some protocols while new analytic models were derived for others. Analytic expressions were derived for describing the list scheduling scheme using some simplifying assumptions.

Simulations were performed to study the validity of these results and it was shown that the analtyic results agreed closely with simulations only for low values of ρ (< .6). A second order correction was presented to bring the analytic results into agreement with simulations for all values of ρ. In cases where correct analytic results could not be obtained, simulations were performed to make a comparative evaluation of the protocols.

Finally, in Chapter 6, the access protocols were compared using specific examples of system parameters. The system parameters C, N_z and message length statistics were shown to be particularly important in determining the relative performance of these protocols.

A common theme running through all of the analysis was the relative importance of propagation and queueing delays in determining system performance (expressed in terms of time delay vs. throughput). It was shown that queueing delays could be reduced if means were found for consolidating packets (or requests for packet transmission) into as small a number of queues as possible. This consolidation, however, was shown to carry various penalties - either increased system complexity and cost (in the case of auxiliary terrestrial links) or additional propagation delays (when satellite order wires are used for packet scheduling).

The curves presented in Chapter 6 represent a parametric picture of the various alternative schemes devised in this work. Since there are a vast number of feasible variations of the satellite-switched multi-beam systems discussed herein, and since the choice of the "best" system for a specific situation depends upon many factors beyond the scope of this first phase study, we have attempted to present an analysis of the

fundamental issues involved in a form general enough to be useful to system designers as well as researchers in the field. By substituting appropriate system parameters into our results it should be possible to evaluate the various trade-offs involved in specific system alternatives. From a more general point of view, the methodology introduced in these studies should be helpful to those wishing to investigate the performance of many other systems in which switching and multiple access are critical issues.

7.2 ISSUES FOR FUTURE STUDY

As is typical in any detailed analytical study, our first phase work has raised at least as many new questions as it has answered. In the second phase we hope to address some of these outstanding issues in addition to applying the results to realistic traffic environments.

As mentioned in Chapter 1, our method of attack thus far has been to concentrate on the problem of serving bursty traffic using packet-switching. In the second phase a prime objective will be the study of systems serving both stream and bursty traffic, which implies integrated circuit- and packet-switched systems. A number of preliminary studies have already been initiated in this direction. These have been focused primarily on a closer look at circuit-switching in a multibeam, wideband satellite environment. In one study we are looking into the scheduling of the satellite switch to satisfy performance requirements specified in terms of circuit blocking probabilities. (Previous studies deal with this problem only on a deterministic basis.)

We are also considering the affect of other system constraints on the scheduling of both circuits and packets.

For example, if adjacent beams overlap producing interference, the satellite switch must be scheduled to avoid illuminating these adjacent beams simultaneously. Other constraints that must be considered are the fact that some circuit users require full-duplex connections and others only simplex links, also some circuit users are wideband, requiring several slots in a TDMA frame, while others require only one.

Circuit-switching in a heterogeneous stream traffic environment (both narrow- and wideband users) has received little attention in the literature thus far. Our preliminary studies have revealed that there are some subtle problems associated with the allocation of bandwidth in these situations. The normal procedure in circuit-switching is to accept a call request when there is capacity (i.e. time slots) available to handle it. Otherwise the call is blocked (or delayed). However, we have shown analytically, that this policy is not always optimal in the sense of achieving maximum channel occupancy. By using methods of Markovian decision processes, optimal policies for allocating calls were derived for some simple examples. Figure 7.1 illustrates the results for a case in which two classes of users are present, the first, requiring one unit of bandwidth (for example, one voice channel), and the second requiring 25 units (equivalent roughly to a T1 carrier). The total bandwidth available is 35 units and there is twelve times as much small user load as large. Average channel occupancy is plotted as a function of offered traffic ρ. (Poisson call arrivals are assumed.) For a significant range of ρ, the optimal policy, which is to block any small users when at least 10 units of capacity are occupied, is clearly superior

to the intuitive approach of accepting all calls (AA) if capacity is available. Fig. 7.2 shows a similar comparison for different parameters. Here the results are even more striking.

This example is included to show that much remains to be learned in the area of satellite systems serving heterogeneous user populations. The problems become still more complex when stream traffic is integrated with bursty data. It is important to study these questions and evaluate system alternatives before any system designs are finalized.

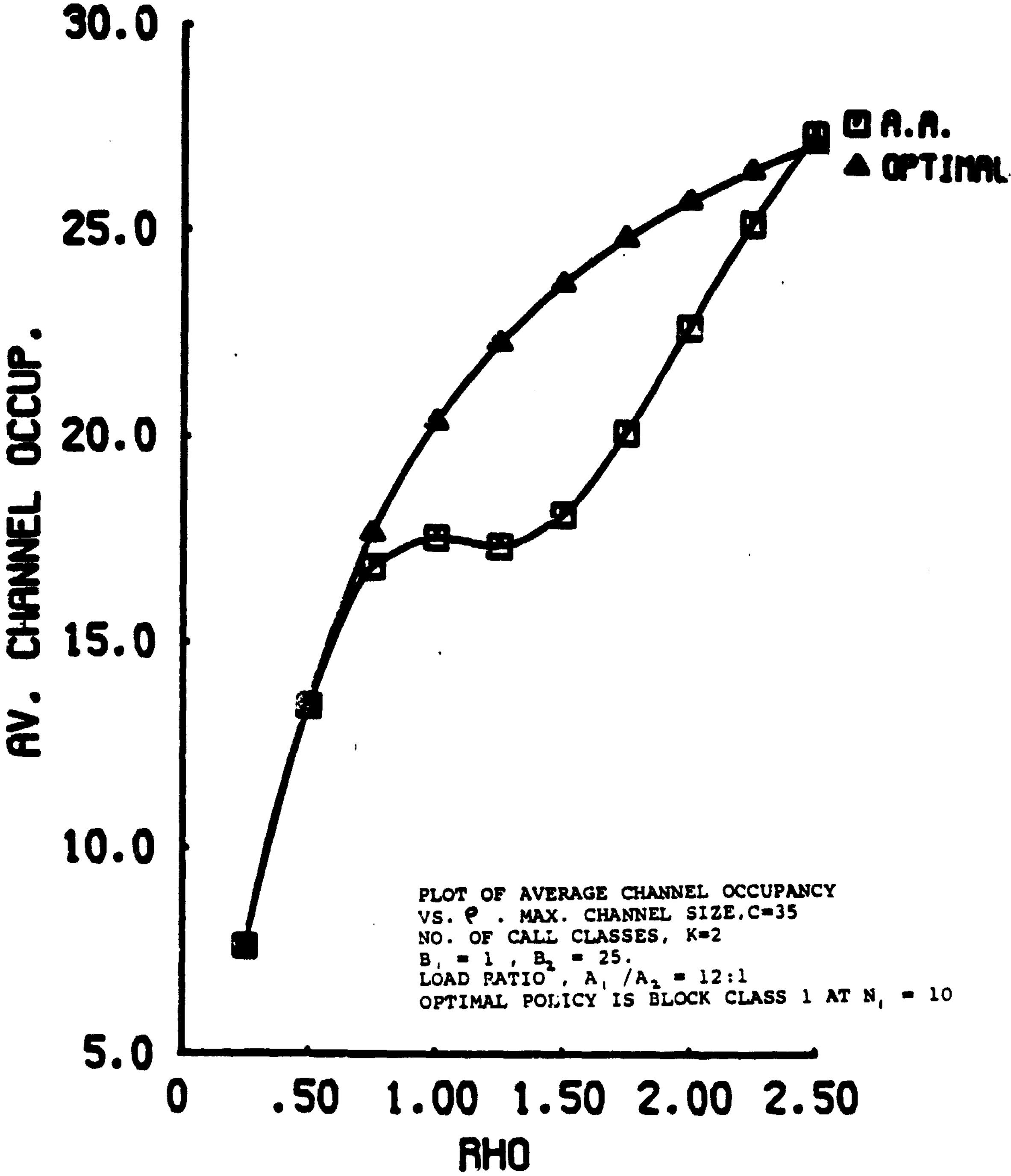


FIGURE 7 1 COMPARISON OF POLICIES IN A HETEROGENEOUS CIRCUIT-SWITCHED SYSTEM

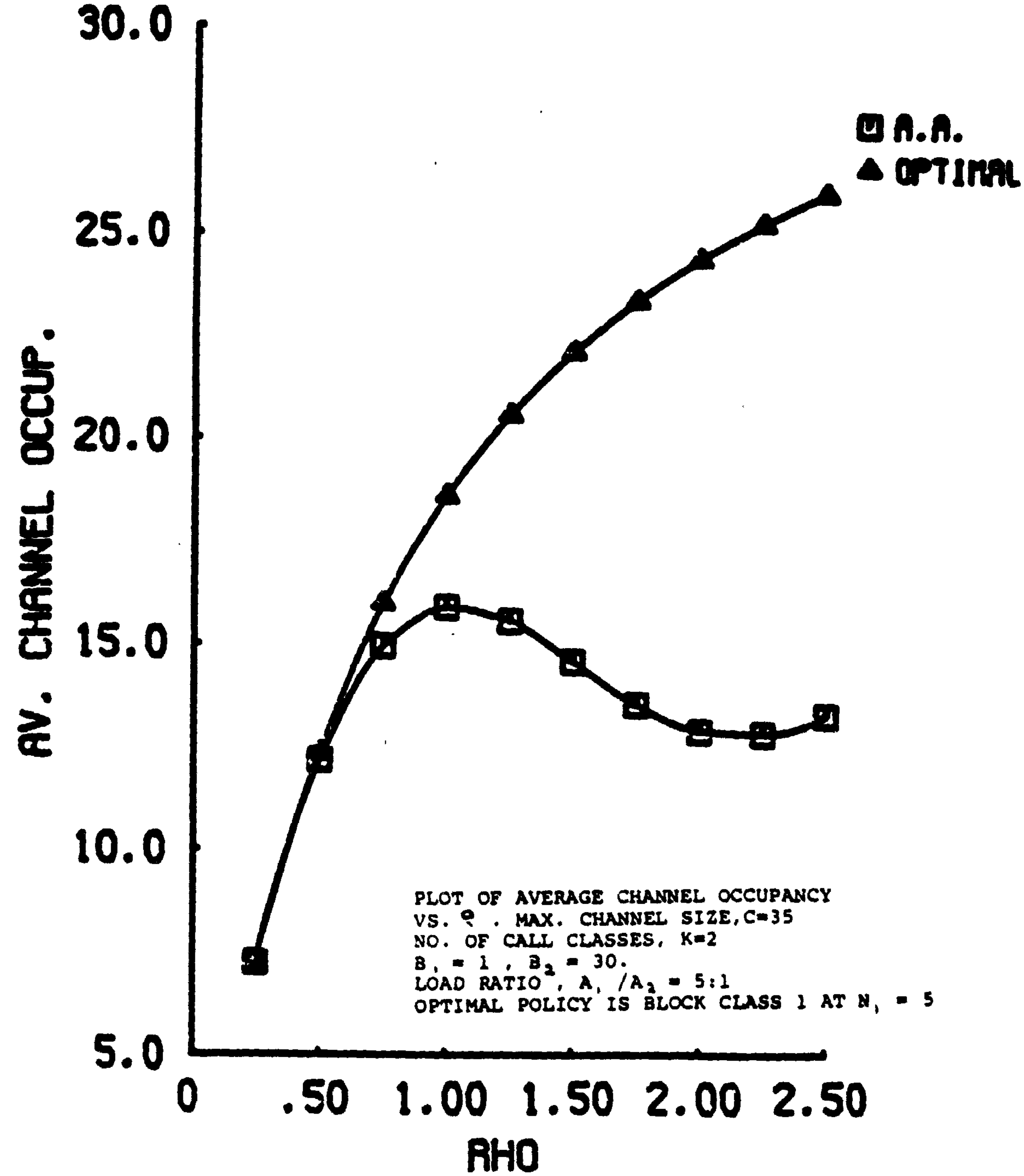


FIGURE 7.2 COMPARISON OF POLICIES IN A HETEROGENEOUS CIRCUIT-SWITCHED SYSTEM

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APPENDIX A

ANALYSIS OF DA/FS SYSTEM

In this appendix, an analytic expression for expected queue length of the request queue for the DA/FS system of Section 3.1 is derived. The approach taken here is similar to that of Konheim and Meister [KON 72]. Average waiting time of the queue is obtained from this expression.

Let us focus attention on the request queue for transmissions from zone i to zone j. The transmission frame, as shown in Fig. 3.1a, has K slots allocated for this traffic. New requests arrive at the beginning of frames at a rate of $\lambda_{i,j}$ requests/frame. (Subscripts i and j are dropped in the following analysis for convenience.)

To analyze the evolution of this queue, we define the following state variables.

q_ℓ = Number of requests in queue just prior to the beginning of the ℓ^{th} frame.

x_ℓ = Number of new requests received in the ℓ^{th} frame.

K = Number of slots/frame available for transmission of this traffic.

The system evolves according to the following equation

$$q_\ell = (q_{\ell-1} - K)^+ + x_\ell \tag{A.1}$$

where $(q_{\ell-1} - K)^+$ denotes the maximum of $(q_{\ell-1} - K)$ and 0.

The state variables q_ℓ, with an initial distribution Π_0 for q_0, form an ergodic Markov chain under the following condition.

$$E\left[x_\ell\right] < K \tag{A.2}$$

We assume that the condition given by equation (A.2) is always satisfied (otherwise, the system will have infinite delays). Using both sides of equation (A.1) as an exponent of z and taking expectations, we

have

$$E\left[z^{q_\ell}\right] = E\left[z^{(q_{\ell-1}-K)^+ + x_\ell}\right] \tag{A.3}$$

The left hand side of this equation is the generating function $Q_\ell(z)$ of queue length. Also, since x_ℓ is independent of $q_{\ell-1}$, we can write equation (A.3) as

$$Q_\ell(z) = E\left[z^{(q_{\ell-1}-K)^+}\right] \cdot P(z) \tag{A.4}$$

where $P(z)$ is the generating function of the packet arrival process.

Also

$$E\left[z^{(q_{\ell-1}-K)^+}\right] = \sum_{r=0}^{K-1} P_r\left[q_{\ell-1} = r\right] + \sum_{r=K}^{\infty} z^{r-K} P_r\left[q_{\ell-1} = r\right]$$

$$= z^{-K}\left\{\sum_{r=0}^{\infty} z^r P_r\left[q_{\ell-1} = r\right] - \sum_{r=0}^{K-1} z^r P_r\left[q_{\ell-1} = r\right] + \sum_{r=0}^{K-1} z^K P_r\left[q_{\ell-1} = r\right]\right\}$$

$$= z^{-K}\left\{Q_{\ell-1}(z) + \sum_{r=0}^{K-1} (z^K - z^r)\, P_r\left[q_{\ell-1} = r\right]\right\} \tag{A.5}$$

where $P_r\left[q_{\ell-1} = r\right]$ denotes the probability that $q_{\ell-1} = r$. Substituting this in equation (A.4), we have

$$Q_\ell(z) = z^{-K} P(z)\left\{Q_{\ell-1}(z) + \sum_{r=0}^{K-1} (z^K - z^r)\, P_r\left[q_{\ell-1} = r\right]\right\} \tag{A.6}$$

The term $P_r\left[q_{\ell-1} = r\right]$ is unknown and to determine this, we define the following function

$$Q(z,w) = \sum_{\ell=0}^{\infty} Q_{\ell}(z) w^{\ell} \tag{A.7}$$

Multiplying equation (A.6) by w^{ℓ} and summing over $1 \le \ell \le \infty$, we get

$$Q(z,w) = \frac{\left[Q_0(z) z^K + wP(z) \sum_{r=0}^{K-1} (z^K - z^r) A_r(w)\right]}{\left[z^K - w\,P(z)\right]} \tag{A.8}$$

$$\text{where} \quad A_r(w) = \sum_{\ell=0}^{\infty} P_r\left[q_{\ell} = r\right] \; w^{\ell} \tag{A.9}$$

The unknowns $\left[A_r(w)\right]_{r=0}^{K-1}$ can be found from the requirement that $Q(z,w)$ be analytic in the contour $|z| < 1$ and $|w| < 1$. By Rouche's theorem [KON 72], the denominator $\left[z^K - w\,P(z)\right]$ has exactly K zeros in this contour. In order for $Q(z,w)$ to be analytic, the numerator must also be zero at these points. We denote these zeros as $\theta_1(w) \ldots \theta_k(w)$, where the numbering has been done so that θ_1 ($= \theta_1(w)$ as $w \to 1$ from below) is 1 and the rest of θ_i's $\neq 1$. Then, from the requirement that the numerator of equation (A.6) must vanish at these zeros, the following equation is obtained [KON 72]

$$Q(z,w) = \frac{z^K Q_0(t) + w(z-1)P(z) \sum_{i=1}^{K} \frac{H_0(\theta_i(w))}{1-\theta_i(w)} \prod_{\substack{t=1 \\ t \neq i}}^{K} \frac{z - \theta_t(w)}{\theta_i(w) - \theta_t(w)}}{z^K - wP(z)} \tag{A.10}$$

Finally, multiplying equation (A.10) by $(1-w)$ and taking the limit as $w \to 1$ from below, the generating function of queue length in steady state is obtained as

$$Q(z) = \frac{(K-\lambda)(z-1)P(z)}{z^K - P(z)} \prod_{t=2}^{K} \frac{z - \theta_t}{1 - \theta_t} \tag{A.11}$$

where λ is the average request arrival rate/frame for this traffic.

The mean of queue length can be found from equation (A.11) as

$$\overline{Q} = \frac{1}{2}\frac{\sigma^2}{K-\lambda} + \frac{1}{2}\mu + \frac{1}{2}\sum_{t=2}^{K}\frac{1+\theta_t}{1-\theta_t} \qquad (A.12)$$

where σ^2 is the variance of the arrival process and μ is

After determining an expression for the average length of request queue, we are in a position to derive average waiting time $\overline{W}_{DA/FS}$ of this queue. A direct application of Little's formula is not possible as this analysis applies only to the situation at the beginning of a frame.

When a request arrives at the queue, all requests that are already in the queue, denoted by Q_p, are scheduled ahead of it. We note that $\overline{Q}_p$ has two components

$$\overline{Q}_p = \overline{Q}_G + \overline{Q}_R \qquad (A.13)$$

where $\overline{Q}_R$ = Average number of requests already in the queue when a group of requests arrive in the mini-slots of a frame.

$\overline{Q}_G$ = Average number of requests within the group that are scheduled ahead of an arriving request.

$\overline{Q}_R$ is obtained easily as

$$\overline{Q}_R = \overline{Q} - \lambda \qquad (A.14)$$

To find $\overline{Q}_G$, we assume that requests arriving within a group are scheduled in random order. Then, $\overline{Q}_G$ is given by

$$\overline{Q}_G = E\left[\frac{(x-1)}{2} \,\middle|\, x > 0\right] \qquad (A.15)$$

To find $\overline{W}_{DF/FS}$ from $\overline{Q}_P$, we make the approximation that the period between consecutive slots is F/K. $\overline{W}_{DA/FS}$ is then given by

$$\overline{W}_{DA/FS} = \frac{F}{K}\ \overline{Q}_P \tag{A.16}$$

Where $\overline{Q}_P$ is given by equation (A.13) together with equations (A.12), (A.14) and (A.15).

APPENDIX B

SUMMARY OF APPLICABLE EQUATIONS

Table B-1 presents a summary of applicable equations for total delay, waiting time (single or multiple packets), queue length, and, frame length, for each of the six access-switching systems analyzed. The results obtained only by simulation are derived from a program with GPSS flow chart as given in Fig. B-1. Fig. B-2 provides a flow chart describing the function implemented in the GPSS program.

Also included here is Fig. B-3, which illustrates the basic concept of memory management referred to on p. 1.20. For explanation of the basic technique, see [CHU 73].

Table B-1 Summary of Applicable Equations for Total Delay $\overline{T}$, Waiting Time $\overline{W}$, Queue Length, and Frame Length

	FA/FS	DA/FS	RA/FS	DA/DS	FA/SF	DA/SF
$\overline{T}$	(2.2)	(2.3)	(2.4),(3.11)	(2.5)	(2.8)	(2.7)
$\overline{W}$	(3.5)	(3.5)	implied in (3.11)	(4.14) also see Secs. 4.4.2 & 4.4.3	(5.3) (5.4)	S* (5.1) (5.2) M* Simulation
Queue Length	(3.3)	(3.3)	not needed	(4.13) also see Sec. 4.4.3 & 4.4.3	Q_M Assumed See Sec. 5.3	Simulation
Frame Length	(2.1)	(2.1a)	(2.1a)	$F = \Delta$	$N_s \Delta$	Δ

*S: Single packets

*M: Multi packets

Fig. B-3 Memory Management Scheme from [CHU 73]

i	$A(B_{i1})$	$A(B_{i\ell})$	b_i
1	3000	6000	1
2	9000	1000	1
3	2000	2000	0
.	-	-	-
.	-	-	-
n	-	-	-

Figure 3A. The Address Translation Table (ATT).

B_{i1} = First block of the message for the i^{th} buffer output (destination), $i = 1,2,...,n$

$B_{i\ell}$ = Last block of the message for the i^{th} buffer output (destination), $i = 1,2,...,n$

n = Total number of buffer outputs or message destinations

$A(B_{i1})$ = Physical address of B_{i1}

$A(B_{i\ell})$ = Physical address of $B_{i\ell}$

b_i = Buffer status bit for the i^{th} buffer output (destination)
= 0 No message in the buffer for the i^{th} output
1 Otherwise

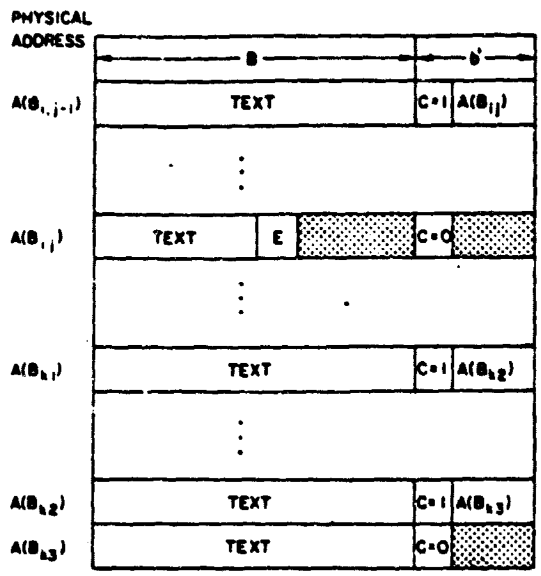


Figure 3B. Buffer Memory (BM)

C = Block continuation bit
= 0 last block
1 otherwise

$A(B_{ij})$ = Physical address of the j^{th} block for the i^{th} buffer output
= linkage pointer

E = End of message character

Dummy information

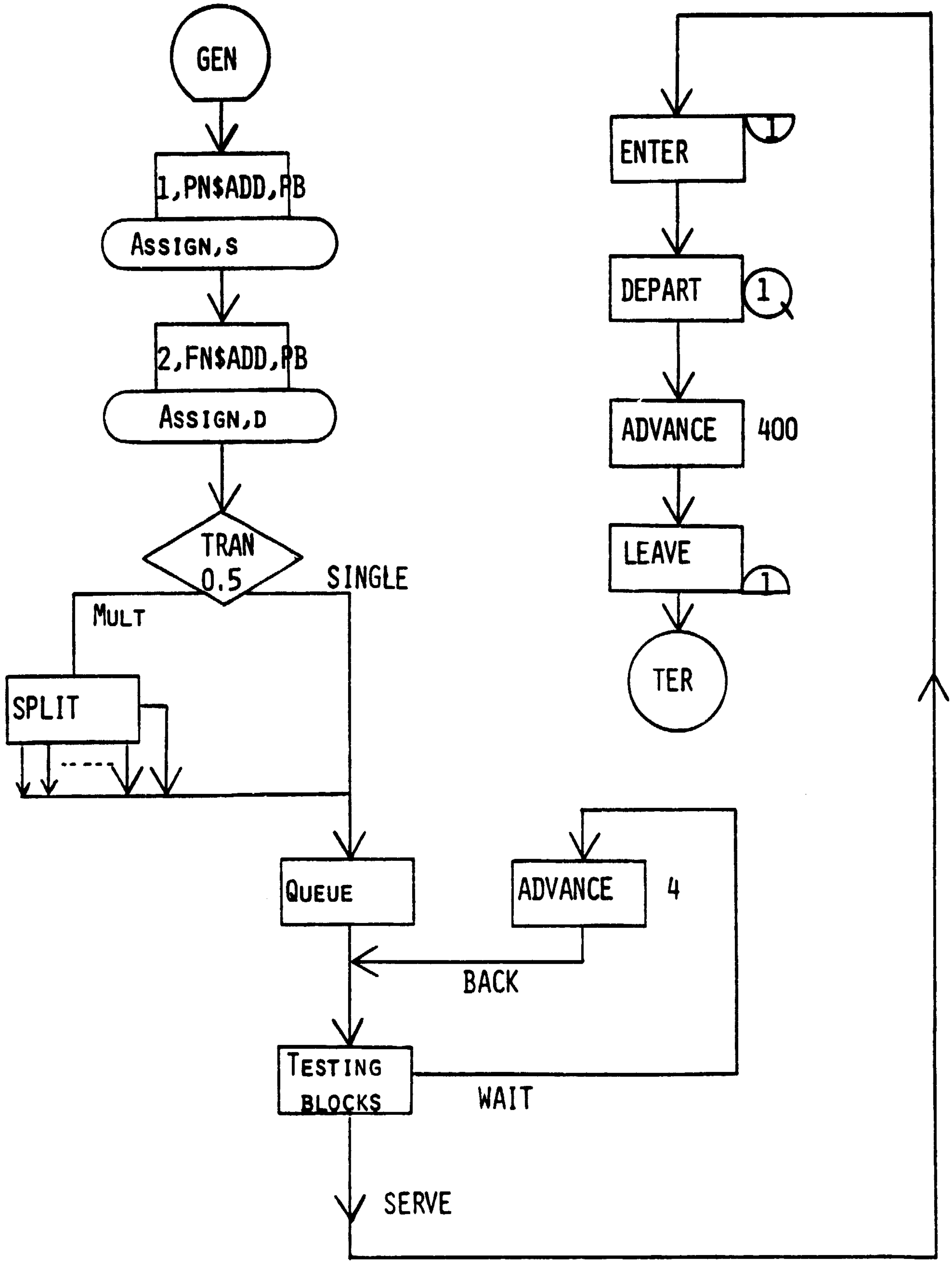
PHYSICAL ADDRESS
$A(B_{ij})$

2000
500
4000
10000
15000
⋮
.

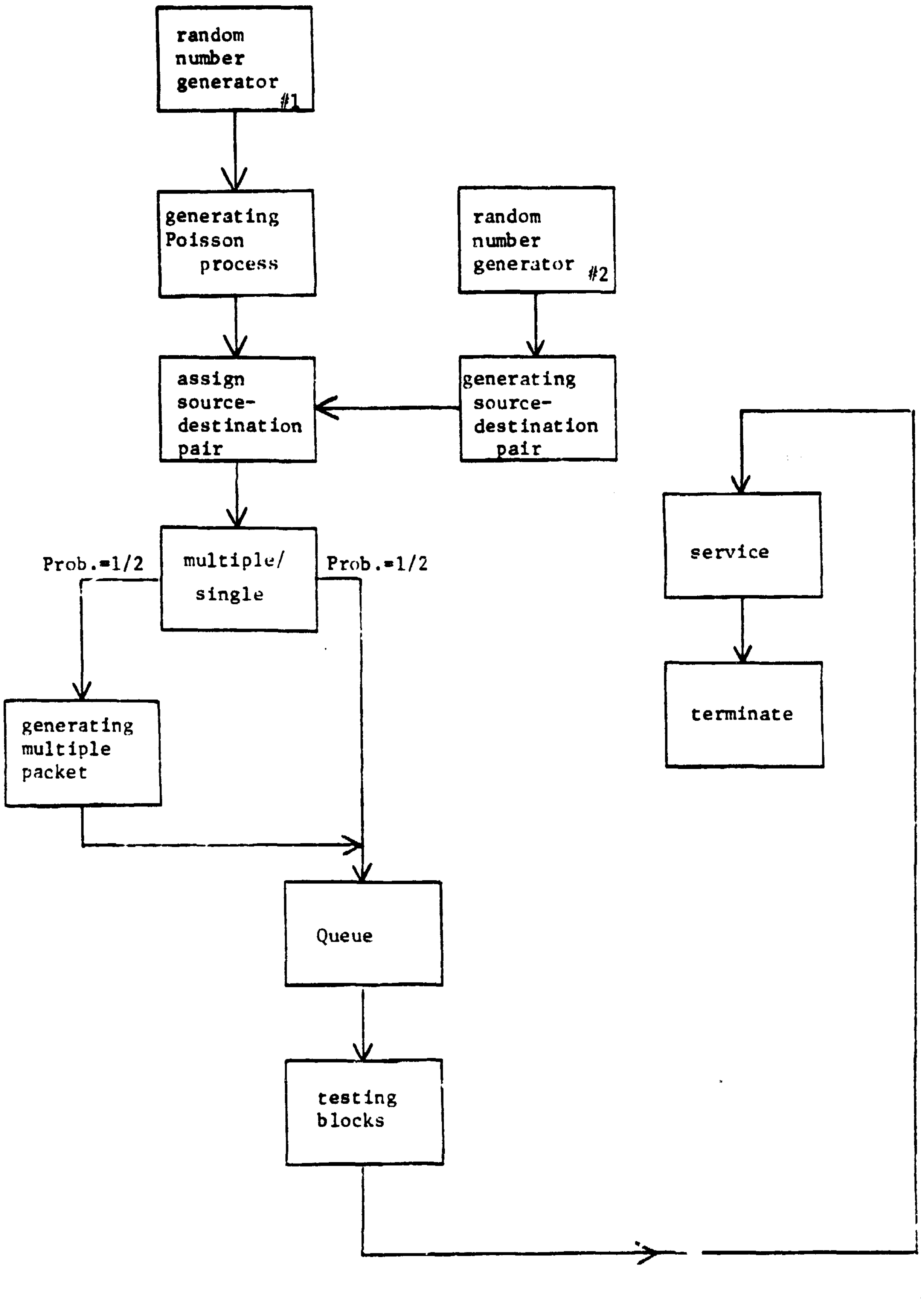
Figure 3C. Block Available List (BAL).

Figure 3. A Shared Buffer Organization.

G.P.S.S. FLOW CHART FOR SIMULATION FIG. B-1



BASIC FLOW CHART FOR SIMULATION FIG. B-2



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